Dkt. #639-B-PCT-US

Application
for
United States Letters Patent

To all whom it may concern:

Be it known that **Nai-Kong CHEUNG**

has invented certain new and useful improvements in

THERAPY-ENHANCING GLUCAN

of which the following is a full, clear and exact description

THERAPY-ENHANCING GLUCAN

This application is a continuation-in-part of International Application No. PCT/US02/01276, Filed 15 January 2002, claiming benefit of U.S. Serial No. 60/261,911, filed on 16 January 2001, the contents of which are incorporated by reference here into this application.

Throughout this application, various references are cited. Disclosures of these publications in their entireties are hereby incorporated by reference into this application to more fully describe the state of the art to which this invention pertains.

BACKGROUND OF THE INVENTION

Monoclonal antibodies (MoAb) selective for tumors have therapeutic potential.[1,2] he introduction of hybridoma technology by Kohler and Milstein in 1975[3] and the advances in molecular biologic techniques have greatly expanded the potential of MoAb in human cancers. Anti-CEA antibody in colorectal cancer,[4] anti-CD20 antibodies in lymphoma,[5] anti-HER2 antibodies in breast cancer,[6] anti-tenascin antibodies in glial brain tumors,[7] MoAb M195 against CD33 in acute leukemia[8] and anti-TAG-72 antibodies in colon cancer[9] have shown efficacy in clinical trials. Our laboratory has developed the MoAb 3F8 which targets the ganglioside GD2 overexpressed on neuroblastoma. 3F8 has been shown to have a high specificity and sensitivity in the radioimmunodetection of minimal residual disease (MRD) in patients with NB,[10] and a significant impact when used as adjuvant therapy.[11]

The immune basis of clinical tumor response to MoAb is at least two fold, direct cytotoxicity and induced immunity. Antibody dependent cell-mediated cytotoxicity (ADCC) and complement-mediated cytotoxicity (CMC) are responsible for the direct killing of tumor cells. On the other hand,

through tumor opsonization[12] or idiotype network,[13] tumor-specific immunity is induced. With this paradigm, how the body eliminates microbial pathogens remains highly relevant in our strategic approach to cancer therapy. Since the first description of innate immunity and acquired immunity model, several components have emerged center stage.[14] Antibodies, complement, phagocytes, and "danger" receptors are core elements of innate immunity while antigen-presenting cells, T and B lymphocytes constitute essential players in acquired immunity. Despite the availability of tumor-selective monoclonal antibodies and the ample supply of phagocytes/natural killers, shrinkage of established tumors following antibody treatment alone, and the acquisition of specific immunity, are not common in both preclinical models and cancer patients. The absence of a danger signal and the diminution of complement action by complement resistance proteins on tumor cells may explain the inefficiency of antibody mediated clinical responses.[15] LPS and beta-glucan, being cell wall components of bacteria and fungus, respectively, are potent danger signals to the immune systems in all life-forms, from Drosophila to man.[16] While LPS is too toxic for human use, β-glucan is a relatively benign structural component extractable from cereals, mushrooms, seaweed and yeasts.[17] They are made up of 1,3-β-D-glucopyranosyl residues along which are randomly dispersed single β-D-glucopyranosyl units attached by 1,6-linkages, giving a comb-like structure. The 1,3-β-backbone and the 1,6-linked branches were thought to be important for their immune effects. Lentinan (from Lentinus edodes, Basidiomycete family) with 1,6 branches at mean of 3 main chain units, is licensed Japan for cancer treatment. Schizophyllan (from Schizophyllum commune, Basidiomycete family) and β-glucan from Baker's yeast (Saccharomyces cerevisiae) have also similar structures. From seaweed,

Laminarin (1,3 β-D-glucan with 1,6-β side chain branching on every 10 glucose subunit along the polymer backbone) has been extracted. Because of its smaller size and water solubility, it was thought to have potential biologic utility. On the other hand β-glucan from barley, oat or wheat have mixed 1,3-β and 1,4-β-linkage in the backbone, but no 1,6-β branches, and generally higher molecular weights and viscosities. In addition, they have not yet been tested for their in vivo immunomodulatory effects in cancer models.

This invention discloses that oral beta-glucans derived from barley or oats can greatly enhance the anti-tumor activity of anti-tumor monoclonal antibodies in xenograft models. Given the low toxicity of oral β-glucan, their role in cancer therapy deserves careful study.

SUMMARY OF THE INVENTION

This invention provides a composition comprising an effective amount of glucan capable of enhancing efficacy of antibodies. In an embodiment, the antibody is a monoclonal antibody. In a further embodiment, the antibody is an antibody against cancer.

The cancer is recognized by antibodies, and which includes but not limited to neuroblastoma, melanoma, non-Hodgkin's lymphoma, Epstein-Barr related lymphoma, Hodgkin's lymphoma, retinoblastoma, small cell lung cancer, brain tumors, leukemia, epidermoid carcinoma, prostate cancer, renal cell carcinoma, transitional cell carcinoma, breast cancer, ovarian cancer, lung cancer colon cancer, liver cancer, stomach cancer, and other gastrointestinal cancers.

This invention further provides the above compositions and a pharmaceutically acceptable carrier, thereby forming pharmaceutical compositions.

This invention also provides a method for treating a subject with cancer comprising administrating the above-described composition to the subject.

This invention provides a composition comprising effective amount of glucan capable of enhancing efficacy of vaccines. In an embodiment, the vaccine is against cancer. This invention also provides the above compositions and a pharmaceutically acceptable carrier, thereby forming a pharmaceutical composition.

This invention also provides a method of treating a subject comprising administrating the above pharmaceutical composition to the subject. In an embodiment, the subject is a human subject. In an embodiment, the vaccine is against

infectious agents. The infectious agents include but are not limited to bacteria, viruses, fungi, or parasites.

This invention provides a composition comprising effective amount of glucan capable of enhancing efficacy of natural antibodies. In an embodiment, the antibodies are against cancer. In another embodiment, the antibodies are against infectious agents. The infectious agents include but are not limited to bacteria, viruses, fungi, or parasites.

This invention provides a composition comprising effective amount of glucan capable of enhancing host immunity. In another embodiment, the immunity is against cancer or infectious agents.

This invention also provides a composition comprising effective amount of glucan capable of enhancing the action of an agent in preventing tissue rejection. In another embodiment, the tissue is transplanted tissue or transplanted organ. In another embodiment, the tissue is the host as in graft-versus-host reactions.

This invention also provides the above compositions, wherein the glucan are. 1,3-1,4 mixed linkage, without 1,6 branches.

The invention further provides the above compositions, wherein the glucan is of high molecular weight. In an embodiment, the molecular weight of the glucan ranges from 250,000 to 450,000 daltons. This invention provides the above compositions, wherein the glucan is derived from barley, oat, wheat or moss.

This invention provides the above compositions, wherein the glucan is stable to heat treatment. In an embodiment, the composition is stable after boiling for 3 hours.

This invention provides the above compositions, wherein oral route is adopted when taken into a subject. In an embodiment, the effective dose is about >= 25 mg/kg/day, five days a week for a total of 2-4 weeks.

DETAILED DESCRIPTION OF THE FIGURES

First Series Of Experiments

Figure 1. Synergistic effect of MoAb and β-glucan in LAN-1 Two million LAN-1 neuroblastoma cells were xenografted subcutaneously in Balb/c athymic mice. Treatment started in groups of 5 mice each, 2 weeks after tumor implantation when visible tumors reached 0.7-0.8 cm diameter. 3F8 group (solid circles) was treated with 200 ug of intravenous 3F8 injected through the retroorbital plexus twice weekly (M and Th). 3F8 + BG group (open circle) was treated with 200 ugi.v.3F8 twice weekly plus oral Barley β-glucan (BG medium viscosity) 400 ug daily by gavage for a total of 21 days. BG group (open triangle) received β-glucan alone, 400 ug po daily for 21 days. Tumor size was measured from the first day of treatment, and the product of the largest diameters expressed as percent of that on day 0 of treatment. While BG alone and 3F8 alone showed no anti-tumor effect, the BG+3F8 group showed highly significant tumor shrinkage and suppression ($p<0.001$).

Figure 2. Synergistic effect of MoAb and β-glucan in NMB-7 Experiment in figure 1 was repeated with the neuroblastoma cell line NMB7, a slower growing line. Again BG alone (open triangle) and 3F8 alone (solid circles) showed no anti-tumor effect, the BG+3F8 group (open circle) showed highly significant tumor shrinkage and suppression ($p<0.001$). Y-axis is relative tumor size in percent and X-axis the number of days from first treatment.

Figure 3. Dose response of intraperitoneal (ip) β-glucan Two million NMB-7 xenografted nude mice were treated at the time of visible tumors with 3F8 alone, normal saline control, or 3F8 plus increasing doses of intraperitoneal BG (4 ug [solid diamond], 40 ug [open square], 400 ug [large

open circle]) or 400 ug of po BG [small open circle], or 400 ug of ip Lentinan [open diamond]. Highly significant tumor shrinkage and suppression was shown in the combination groups except at 4 ug of BG dose. Oral BG appeared to be more effective than ip BG.

Figure 4. Dose response of oral β-glucan NMB-7 xenografted in nude mice were treated as in figure 3 except that dose response of oral β-glucan (4ug [open diamond], 40 ug [open triangle], 400 ug [open circle]) was compared to 400 ug of ip BG [solid square]. Control group received saline [solid circle]. 400 ug po was again highly significant in eradicating or suppressing tumor growth. 400 ip appeared to be as effective as 40 ug po. 4 ug was the least effective.

Figure 5. Dose response of oral β-glucan in LAN-1 Five million LAN-1 cells were planted subcutaneously. Tumor growth was more rapid compared to 2 million NMB-7 cells. Again 4 ug [solid squares], 40 ug [solid triangle] were no different from controls. Only 400 ug po [open circle] and 4000 ug po [open square] showed significant tumor eradication or suppression.

Figure 6. Comparison of various β-glucans β-glucan [400 ug po qd] derived from barley [7 days/wk open circle, M-F/week open triangle], Maitake mushrooms [solid triangles], laminarin [open squares] were compared in their synergism with antibody 3F8 against NMB-7 subcutaneous xenografts.

Figure 7. More comparison of various β-glucans β-glucans (400 ug po qd) from different barley lots [large open circle, small open circle], lentinan [open diamond], PSK [cross] were compared to mannan [solid square], 3F8 only [open triangle] or no treatment [solid circle]. Only BG

from barley showed syngergistic anti-tumor effect with antibody 3F8 against LAN-1 xenografts.

Figure 8. D-fraction Maitake Mushroom β-glucan [open square] had no anti-tumor effect when compared to barley β-glucan alone [solid circle], 3F8 alone [open triangle], in contrast to barley β-glucan plus 3F8 [open circle] which was highly effective.

Figure 9. Barley β-glucan of large molecular weight is more effective β-glucan of 40K [solid square], 123K [open triangle], 183K [open square], 254K [open diamond], and 359K [open circle] were tested at 40 ug po daily dose in combination with 3F8 against LAN-1 subcutaneous xenografts. The larger the size of the β-glucan, the more effective the synergistic effect.

Figure 10. β-glucans of low molecular weight and low viscosity was ineffective β-glucans of various viscosities [40 ug po qd] derived from barley and oats were tested in combination with 3F8 against LAN-1 subcutaneous xenografts. Barley medium viscosity [large open circle], barley high viscosity [open square], oat medium viscosity [small open circle, dotted line], and oat high viscosity [open square, dotted line] were all effective in shrinking and suppressing tumor growth, in contrast to low viscosity barley β-glucan [solid square].

Figure 11. Removal of NK cells by anti-Asialo GM1 antiserum in LAN-1 xenograft decreased but did not eliminate the anti-tumor effect of barley β-glucan plus 3F8.

Figure 12. Removal of NK cells by anti-Asialo GM1 antiserum in NMB-7 x nograft again decreased but did not eliminate the anti-tumor effect of barley β-glucan plus 3F8.

Figure 13. 3F8-F(ab`)2 fragment [solid square], nonspecific human IgG [small solid square] or IgM [solid diamond] have no anti-tumor effect while 3G6 (IgM anti-GD2, open circle) was almost as effective as 3F8 (IgG3 anti-GD2, open triangle).

Figure 14. Barley β-glucan synergizes with R24 anti-GD3 antibody in SKMel28 melanoma xenografts in nude mice In contrast to β-glucan control [solid diamond], and R24 control [solid circle], the combination of R24 and β-glucan [open circle] significantly suppressed tumor growth.

Figure 15. Barley β-glucan synergizes with 3F8 anti-GD2 antibody against B16D14 murine melanoma in C57Bl/6 mice In contrast to saline control [solid circle], β-glucan control [solid triangle], and 3F8 control [solid square], the combination of 3F8 and β-glucan [open circle] significantly suppressed tumor growth.

Figure 16. Barley β-glucan synergizes with 3F8 anti-GD2 antibody against B16D14-KbKd murine melanoma in C57Bl/6 mice In contrast to 3F8 control [solid circle], the combination of 3F8 and β-glucan [open circle] significantly suppressed tumor growth.

Figure 17. Barley β-glucan plus 3F8 did not affect GD2-negative B16 melanoma in C57Bl/6 mice The combination of 3F8 and β-glucan [solid circle] did not significantly suppress tumor growth when compared to controls [open circle].

Figure 18. Barley β-glucan synergizes with 3F8 anti-GD2 antibody against E14 murin lymphoma in C57Bl/6 mice In contrast to control [solid circle], the combination of 3F8 and β-glucan [open circle] significantly suppressed tumor growth.

Figure 19. BARLEY Glucan syngergizes with 3F8 in prolonging survival from NMB7 neuroblastoma. Nude mice (n=21) with established neuroblastoma NMB7 xenografts treated with 3F8 and barley β-glucan (open circles) had significantly longer median survival >300 days compared to 30 days in the control mice (solid triangle) treated with saline alone, 3F8 alone, or β-glucan alone ($p<0.001$). Long-term survival was 56% in the treatment group and 5% in the control group.

Figure 20. BARLEY glucan synergizes with 3F8 in prolonging survival from LAN-1 neuroblastoma. In nude mice bearing established LAN1 xenografts median survival increased from 20 days in the control group (n=38, solid triangles) to 42 days in the 3F8 plus glucan group (n=48, open circles, $p<0.001$).

<u>**Second Series of Experiments**</u>

Figure 1. Synergistic effect of MoAb and β-glucan in neuroblastoma xenografts. Two million neuroblastoma cells (1A: LAN-1, 1B: NMB7, 1C:SK-N-ER) were xenografted subcutaneously in athymic Balb/c mice. Treatment started in groups of 5 mice each, 2 weeks after tumor implantation when visible tumors reached 0.7-0.8 cm diameter. 3F8 group (solid circles) was treated with 200 ug of intravenous 3F8 injected through the retroorbital plexus twice weekly (M and Th). 3F8 + BG group (open circle) was treated with 200 ugi.v.3F8 twice weekly plus oral β-glucan (BG) 400 ug daily by gavage for a total of 21-29 days. BG group (open triangle) received 400 ug oral β-glucan alone. Tumor size

was measured from the first day of treatment, and the product of the largest diameters expressed as percent of the size on day 0 of treatment. Vertical bars represent standard errors, which were similar for the glucan and the 3F8 alone groups. While BG alone and 3F8 alone showed no anti-tumor effect, the BG+3F8 group showed highly significant tumor shrinkage and suppression ($p<0.01$).

Figure 2. Dose response of intraperitoneal (ip) β-glucan. Two million NMB7 xenografted athymic nude mice were treated at the time of visible tumors with 3F8 alone, normal saline control, or 3F8 plus increasing doses of intraperitoneal BG (4 ug [solid diamond], 40 ug [open square], 400 ug [large open circle]) or 400 ug of po BG [small open circle]. Highly significant tumor shrinkage and suppression was shown in the combination groups except at 4 ug of BG dose. Oral BG appeared to be more effective than ip BG.

Figure 3. Dose response of oral β-glucan. NMB7 xenografted in nude mice were treated as in Figure 3 except that dose response of oral β-glucan (4ug [open diamond], 40 ug [open triangle], 400 ug [open circle]) was compared to 400 ug of ip BG [solid square]. Control group received saline [solid circle]. 400 ug po was again highly significant in eradicating or suppressing tumor growth. 400 ip appeared to be as effective as 40 ug po. 4 ug was the least effective.

Figure 4. Removal of NK cells by anti-Asialo GM1 antiserum on β-glucan effect in LAN-1 xenografts decreased but did not eliminate the anti-tumor effect of β-glucan plus 3F8.

Figure 5. Barley β-glucan syngergized with 3F8 in prolonging survival from NMB7 neuroblastoma. Nude mice (n=22) with established neuroblastoma NMB7 xenografts treated with 3F8 and barley β-glucan (solid line) had significantly longer median survival (median 166 days)

compared to control mice (n=34, broken line, median 30 days) treated with saline alone (n=10), 3F8 alone (n=8), or β-glucan alone (n=16) (p<0.001). Long-term survival was 47% in the treatment group and 3% in the control group.

Figure 6. Barley β-glucan synergized with 3F8 in prolonging survival from LAN-1 neuroblastoma. In nude mice bearing established LAN-1 xenografts, median survival increased from 21 days in the control group (n=55, broken line) to 54 days in the 3F8 plus glucan group (n=82, solid line, p<0.001).

Third Series of Experiments

Figure 1. Oral β-glucan syngergizes with 3F8 in prolonging survival from neuroblastoma. Nude mice (n=22, solid line) with established NMB7 xenografts (0.7-0.8 cm diameter tumor at the beginning of treatment) were treated with 3F8 (200 ug twice a week iv) and 400 ug of β-glucan po daily for a total of 3 weeks. Control mice received either saline alone (n=10, broken line), 3F8 alone (n=8, dashed line), or β-glucan (n=16, dotted line) alone. Median survival was 30 days in control groups and 166 days in the treatment (3F8 plus β-glucan, n=22) group (p<0.001). Ten (45%) in the combination group survived long term with a median follow-up of 248 days. Only one mouse in any of the control groups (<5%) remained alive during the experiment.

Figure 2. Syngery of Oral barley β-glucan with (A) R24 (anti-GD3) antibody against SKMel28 melanoma xenografts in nude mice. In contrast to β-glucan control [solid diamonds], and R24 control [solid circles], the combination of R24 and β-glucan [open circles] significantly suppressed tumor growth (tumor growth rate reduced for combination treatment by 1.2%, 95% CI -0.1%, 2.5%, p=0.06) **(B)** 528 (anti-EGF-R) MoAb against epidermoid carcinoma A431 xenografts in nude mice. In contrast to β-glucan + 455

(IgG1 noncomplement fixing) control [solid sqaures], and 528 MoAb alone [solid circles], the combination of 528 MoAb and β-glucan [open circles] significantly suppressed tumor growth (tumor growth rate reduced for combination treatment by 1.4%, 95% CI -0.7%, 3.5%, p=0.17). **(C)** Herceptin (anti-HER2) antibody against human breast carcinoma BT474 xenografts in nude mice. In contrast to control [n=4,solid circles], Herceptin [n=9,open squares], or β-glucan control [n=7,solid squares], the combination of Herceptin and β-glucan [n=12,open circles] significantly suppressed tumor growth (tumor growth rate reduced for combination treatment by 1.9%, 95% CI 0.7%, 3%, p=0.002).

Fourth Series of Experiments

Figure 1A. Baseline MIBG scan of patient 5. Extensive osseous metastasis can be seen in the femora, fibulae, pelvis, rib, left scapula, right clavicle, humeri, skull and spine. Heart, liver, stomach and colon uptakes are physiologic.

Figure 1B. MIBG Scan of same patient 2 months later, following a single cycle of therapy. Areas of metastases have significantly improved.

Fifth Series of the Experiment

Figure 1. Subcutaneous xenograft growth in SCID mice. SCID mice with established subcutaneous Daudi (n=9) (Fig A), Hs445 (n=5)(Fig. B), EBV-derived LCL (n=9) (Fig C) and RPMI 6666 (n=10; data not shown) xenografts were treated either with 200ug intravenous rituximab twice weekly for 8 doses (■),400ug (1→3), (1→4)-D-β-glucan administered orally via intragastric gavage daily for 29 days (Δ) or a combination of rituximab and (1→3), (1→4)-D-β-glucan (x), or left untreated (◆). Percentage tumor growth is plotted on y-axis

and days after treatment was commenced on x-axis. Error bars represent SEM and have been shown only for rituximab alone and combination groups. For all xenografts, only combination treatment was associated with reduction in tumor growth. The reduction in tumor growth per day in the group receiving β-glucan in addition to rituximab compared to rituximab alone was 2.0% (95% CI 1.3-2.7%; $p<0.0005$) for Daudi, 0.8% for EBV-derived LCL (95% CI 0.4-1.2%; p<=001), 2.2% for Hs445 (95% C.I. 1.2%-3.2%; $p=0.0009$), and 1.8% for RPMI6666 (95% CI 1.0-2.7 %; $p<0.0002$; data not shown) xenografts.

Figure 2. Survival in SCID mice with disseminated lymphoma xenografts. $5x10^6$ Daudi (Fig. 2A) or Hs445 (Fig. 2B) cells in 100 μl normal saline were injected intravenously (IV) into SCID mice. Mice were treated either with 200ug intravenous rituximab twice weekly for 8 doses (---), 400ug (1→3), (1→4)-D-β-glucan administered orally via intragastric gavage daily for 29 days (....) or a combination of rituximab and (1→3), (1→4)-D-β-glucan (——), or left untreated (▬) commencing 10 days after tumor implantation. Tumors grew systemically and mice became paralyzed when tumor cells infiltrated the spinal canal, resulting in hind-leg paralysis. Mice were sacrificed at onset of paralysis or when animals lost 10% of their body weight. Kaplan-Maier survival curves for the various groups are shown in Figures 2A (Daudi) and 2B (Hs445). Mice treated with a combination of (1→3), (1→4)-D-β-glucan and rituximab had a significantly increased survival when compared to all other treatment groups ($p<0.0005$ for Daudi and $p=0.001$ for Hs445) or when compared to rituximab alone ($p<0.0005$ for Daudi and $p=0.01$ for Hs445). Median survival for mice with no treatment, rituximab alone, BG, and rituximab+BG groups was 27,71,43 and 124 days respectively for Daudi xenografts, and 12, 16, 31 and 243 days respectively for Hs445 xenografts.

DETAILED DESCRIPTION OF THE INVENTION

This invention provides a composition comprising an effective amount of glucan capable of enhancing efficacy of antibodies.

In an embodiment, the antibody is a monoclonal antibody. In a further embodiment, the antibody is an antibody against cancer. In another embodiment, the antibody is a tumor-binding antibody. In a further embodiment, the antibody is capable of activating complement. In a still further embodiment, the antibody is further capable of activating the antibody dependent cell-mediated cytotoxicity.

In an embodiment, the antibody is directed at the epidermal growth factor receptor. In a further embodiment, the antibody is 528 or C225.

In another embodiment, the antibody is directed to a ganglioside. In a further embodiment, the ganglioside is GD3. In a still further embodiment, the antibody is R24.

In a separate embodiment, the ganglioside is GD2. In a further embodiment, the antibody is 3F8.

In an embodiment, the antigen recognized by the antibody is CD20. In a further embodiment, the antibody is Rituximab.

In another embodiment, the antigen is CD25. In a further embodiment, the antibody is Dacluzimab.

In a separate embodiment, the antigen is Her2/neu. In a further embodiment, the antibody is Herceptin.

In another embodiment, the antigen is CD22. In a further embodiment, the antibody is Epratuzumab.

The cancer is recognized by antibodies, and it includes but is not limited to neuroblastoma, melanoma, non-Hodgkin's lymphoma, Epstein-Barr related lymphoma, Hodgkin's lymphoma, retinoblastoma, small cell lung cancer, brain tumors, leukemia, epidermoid carcinoma,[40] prostate cancer,[40,41] renal cell carcinoma,[40] transitional cell carcinoma,[40] breast cancer,[42,43] ovarian cancer,[40] lung cancer, colon cancer,[40] liver cancer, stomach cancer, and other gastrointestinal cancers.

This invention further provides the above compositions and a pharmaceutically acceptable carrier, thereby forming pharmaceutical compositions.

This invention also provides a pharmaceutical composition comprising a combination as described above and a pharmaceutically acceptable carrier. For the purposes of this invention, "pharmaceutically acceptable carriers" means any of the standard pharmaceutical carriers. Examples of suitable carriers are well known in the art and may include, but are not limited to, any of the standard pharmaceutical carriers such as a phosphate buffered saline solution and various wetting agents. Other carriers may include additives used in tablets, granules and capsules, etc. Typically such carriers contain excipients such as starch, milk, sugar, certain types of clay, gelatin, stearic acid or salts thereof, magnesium or calcium stearate, talc, vegetable fats or oils, gum, glycols or other known excipients. Such carriers may also include flavor and color additives or other ingredients. Compositions comprising such carriers are formulated by well-known conventional methods.

This invention also provides a method for treating a subject with cancer comprising administrating the above-described composition to the subject.

This invention provides a composition comprising an effective amount of glucan capable of enhancing efficacy of vaccines. In an embodiment, the vaccine is against cancer.

This invention also provides the above compositions and a pharmaceutically acceptable carrier, thereby forming a pharmaceutical composition.

This invention also provides a method of treating a subject comprising administrating the above pharmaceutical composition to the subject. In an embodiment, the subject is a human subject.

In an embodiment, the vaccine is against infectious agents. The infectious agents include but are not limited to bacteria, viruses, fungi, or parasites.

This invention provides a composition comprising an effective amount of glucan capable of enhancing efficacy of natural antibodies.

In an embodiment, the antibodies are against cancer.

In another embodiment, the antibodies are against infectious agents. The infectious agents include but are not limited to bacteria, viruses, fungi, or parasites.

This invention provides a composition comprising an effective amount of glucan capable of enhancing host immunity. In another embodiment, the immunity is against cancer or infectious agents.

This invention also provides a composition comprising an effective amount of glucan capable of enhancing the action of an agent in preventing tissue rejection.

In an embodiment, the agent is an antibody. In a further embodiment, the antibody modulates T-cell function. In a

still further embodiment, the antibody is anti-CD25 or anti-CD3.

In a separate embodiment, the antibody modulates B-cell function. In another embodiment, the antibody is anti-CD20.

In another embodiment, the tissue is transplanted tissue or transplanted organ. In another embodiment, the tissue is the host as in graft-versus-host reactions.

This invention also provides the above compositions, wherein the glucan are 1,3-1,4 mixed linkage, without 1,6 branches.

The invention further provides the above compositions, wherein the glucan is of high molecular weight. In an embodiment, the molecular weight of the glucan ranges from 250,000 to 450,000 daltons.

This invention provides the above compositions, wherein the glucan is derived from barley, oat, wheat, or moss.

This invention provides the above compositions, wherein the glucan is stable to heat treatment. In an embodiment, the composition is stable after boiling for 3 hours.

This invention provides the above compositions, wherein the oral route is adopted when administered a subject. In an embodiment, the effective dose is about >= 25 mg/kg/day, five days a week for a total of 2-4 weeks.

This invention provides a composition for oral uptake of substance comprising an appropriate amount of carbohydrates. In an embodiment, the carbohydrate is glucan.

When administered orally, glucan is taken up by macrophages and monocytes which carry these carbohydrates to the marrow and reticuloendothelial system from where they are released,

in an appropriately processed form, onto myeloid cells including neutrophils, and onto lymphoid cells including natural killer (NK) cells. This processed glucan binds to CR3 on these neutrophils and NK cells, activating them in tumor cytotoxicity in the presence of tumor-specific antibodies.

Since macrophage and monocytes ingest glucan (whether soluble, gel or particle) from the gut, glucan is a potential conduit for gene therapy. Unlike proteins, DNA or plasmids are relatively heat-stable, and can be easily incorporated into warm soluble barley glucan which gels when cooled to room or body temperature. When mice are fed these DNA-glucan complexes, reporter genes can be detected in peripheral blood monocytes and macrophages within days. More importantly these reporter genes are expressed in these cells, a few days after ingestion of these DNA complexes. These findings have potential biologic implications. Glucan and similar carbohydrates may be conduits for DNA or plasmids to get into the human body. Oral glucan may be a convenient vehicle for correcting genetic defects of macrophages/monocytes, or administering genetic vaccines.

As it can easily be appreciated by an ordinary skilled artisan, other carbohydrates capable of functioning like glucan could be identified and used in a similar fashion. One easy screening for such carbohydrates can be established using glucan as the positive control.

The glucan includes but is not limited to 1, 3-1, 4 mixed linkage-glucan, and the glucan is of high molecular weight.

The substance which could be delivered orally includes but is not limited to peptides, proteins, RNAs, DNAs, and plasmids. Other small molecules and compounds may be used as well.

This invention further provides a pharmaceutical composition comprising an effective amount of the above composition and a pharmaceutically acceptable carrier.

This invention also provides a method for introducing substance into cells comprising contacting the above compositions with said cells. One can use reporter genes or other markers to assess the efficiency of the said introduction. Reporter genes or markers are well known in the molecular biology field. In addition, this invention provides a method for introducing substance into a subject comprising administering to the subject an effective amount of the above compositions.

This invention provides a method for treating a subject comprising administering to the subject an effective amount of the above composition. In an embodiement, the method further comprises the substance.

This invention provides a method for treating a subject with genetic disorder comprising administering to the subject an effective amount of the above-described composition and a substance capable of correcting said genetic disorder. The substance includes but is not limited to a peptide, protein, RNA, DNA, plasmid and other small molecule and compound.

The invention will be better understood by reference to the Experimental Details which follow, but those skilled in the art will readily appreciate that the specific experiments detailed are only illustrative, and are not meant to limit the invention as described herein, which is defined by the claims which follow thereafter.

EXPERIMENTAL DETAILS

Materials and Methods

Cell lines Human neuroblastoma cell lines LA-N-1 was provided by Dr. Robert Seeger, Children's Hospital of Los Angeles, Los Angeles, CA and NMB7 by Dr. Shuen-Kuei Liao (McMaster University, Ontario, Canada). Neuroblastoma cell lines SKNHM, SKNHB, SKNJD, SKNLP, SKNER, SKNMM, SKNCH and SKNSH were derived from patients with metastatic disease treated at Memorial Sloan-Kettering Cancer Center (MSKCC), New York, NY. Other cells lines, Daudi, RMPI 6666, SKMel-28, A431, B16 were derived from American Type Culture Collection (ATCC), Rockville, MD. The cell lines B16, B16D14 were kindly provided by Dr. Kenneth Lloyd of Memorial Sloan-Kettering Cancer Center. Kb transfected (B16D14Kb) and (Kb + Kd) transfected (B16D14KbKd) were kindly provided by Dr. Michel Sadelain, MSKCC. Cell lines were cultured in 10% defined calf serum (Hyclone, Logan, UT) in RPMI with 2 mM L-glutamine, 100 U/ml of penicillin (Sigma, St. Louis, MO), 100 ug/ml of streptomycin (Sigma), 5% CO2 in a 37°C humidified incubator. Normal human mononuclear cells were prepared from heparinized bone marrow samples by centrifugation across a Ficoll-Hypaque density separation gradient.

Antibodies Monoclonal antibodies 3F8 (mouse IgG3) and 3G6 (mouse IgM), and 8H9 (mouse IgG1) reactive with neuroblastoma have been previously described. They were produced by as ascites and purified by affinity chromatography: protein A (Pharmacia, Piscataway, NJ) for 3F8,[18] protein G (Pharmacia) for 8H9,[19] and C1q-sepharose (Pierce Chemicals) for 3G6.[18,20] These antibodies are >90% pure by SDS-PAGE. F(ab`)2 fragments were prepared by pepsin digestion as previously reported.[21] Anti-GD3 antibody (R24) was kindly provided by Dr. Paul Chapman of MSKCC.[22] FLOPC21, an IgG3 myeloma, was purchased from Sigma

Chemicals, St. Louis, MI. TIB114 (N.S.7) a hybridoma secreting an IgG3 control antibody was obtained from ATCC. Rabbit anti-asialo-GM1 antibody (Wako Pure Chemical Industries, Ltd, Osaka, Japan) diluted to 1 mg/ml of protein was administered at 200 ul ip on days 0, 1, 2, 7, 14, 21. Rituximab, anti-CD20 antibody was purchased from Genentech, Inc., CA.

Indirect immunofluorescence 1 million target cells were washed in PBS and then spun at 180 x g for 5 min. The pellets were then reacted with 100 μl of 15μg/ml 8H9 at 4°C for 1 hour. After washing the cells with PBS they were allowed to react with 100μl FITC-conjugated goat F (ab`)2 anti- mouse IgG + IgM, (Biosource International, Camarillo, CA) at 4° C.[18] Flow cytometric analysis was performed using FACSCalibur Immunocytometer (Becton-Dickinson Immunocytometry Systems, San Jose, CA).

Glucan 1,3-1,4-β-glucan derived from barley, 1,3-1,6--β glucan (Laminarin) from seaweed (Laminaria digitata), and mannan were purchased from Sigma Co. 1,3-1,6-β-glucan (Lentinan) was obtained from Drug Synthesis and Chemistry Branch, Developmental Therapeutics Program, Division of Cancer Treatment, National Cancer Institute, Bethesda, MD. Maitake mushroom glucan (containing 1,3-1,6-β-glucan extracted from Grifola frondosa) D-fraction was obtained from Maitake Products Inc., Paramus, NJ. Barley and oats β-glucans of various molecular sizes (measured by high performance size-exclusion chromatography [HPSEC] with multiple angle laser scattering [MALLS] detection) and viscosities (measured in cSt units) were obtained from Megazyme International Ireland Ltd., Bray, County, Ireland. Barley glucan was dissolved by boiling for 10 minutes in normal saline. A stock solution of Lentinan in DMSO (Sigma) was diluted in water before use.

Mice and treatment Athymic Balb/c and C57Bl/c mice were purchased from Jackson Laboratories, Bar Harbor, ME, and CB-17 SCID from Taconic. Tumor cells were planted (1-5 x10(6) cells) in 100ul of Madrigel (Sigma Co)subcutaneously. Following implantation, tumor sizes (maximum width and lengths) were measured. Tumor size was calculated as product of the 2 perpendicular diameters. Treatment studies started when tumor diameter reached 0.7 to 0.8 cm, usually by 14-21 days of tumor implantation. Mice received antibody treatment intravenously (by retroorbital injection) twice weekly and glucan by gavage every day for a total 3-4 weeks (21-8 days of glucan and 6-8 doses of antibody). Mice were weighed once a week and tumor size measured twice a week. Mice were sacrificed when tumors reached sizes that interfered with their well-being.

^{51}Chromium (51Cr) release assay[23] In brief, $2x10^3$ of 51Cr-labeled target cells were mixed with effector cells in a final volume of 0.2 ml of medium in 96-well flat-bottomed microtiter plates (Costar, Cambridge, MA). The plates were incubated for 4 h at 37°C in 5%CO2 and then centrifuged. 100ul of assay supernatant was counted in a gamma counter. Target cell spontaneous chromium release ranged from 10 to 25%.

RESULTS

Barley glucan synergizes with anti-GD2 antibody 3F8 in eradicating human neuroblastoma. 3F8 is a murine IgG3 monoclonal antibody specific for ganglioside GD2. It activates mouse and human complement, and mediates effective ADCC against human neuroblastoma cells in vitro. Barley glucan when administered orally at 400 ug qd had no appreciable effect on tumor growth compared to antibody 3F8 giveni.v.alone. However, when barley glucan and 3F8 were used in combination, tumor growth was near totally

suppressed. In >40% of mice, NMB7 tumors remained permanently suppressed even when treatment was stopped after 21 days. Similar observations were made with neuroblastoma cell lines derived from different sources: NMB7, LAN-1 (**Figures 1** and **2**) and SK-N-ER (data not shown). Barley glucan was equally effective when administered orally or intraperitoneally. In contrast, for the GD2-negative rhabdomyosarcoma, HTB82, 3F8 plus β-glucan treatment was ineffective (data not shown).

Dose response curve for ip barley glucan. When the dose of intraperitoneal barley glucan was decreased 10-fold from 400 ug, it was clear that 4 ug was no longer effective in synergizing with MoAb 3F8 in suppressing NMB7 growth. Interestingly, both ip lentinan and po glucan (at 400 ug po qd) were also effective (**Figure 3**).

Oral barley glucan is as effective as ip glucan When oral barley glucan was studied in NMB7 tumor (**Figure 4**) followed after treatment for 80 days, similar dose response was found, i.e. while 400 ug oral regimen was curative, breakthroughs were seen for the other dose levels, with 4 ug oral dose escaping sooner than 40 ug. Interestingly, 400 ug ip was only as effective as the 40 ug oral group, with late breakthrough tumor growths around the same time, unlike the 400 ug po group, where all tumors remained suppressed despite stopping all therapy after 21 days. Using the LAN1 tumor model, both 4 and 40 ug glucan were ineffective compared to 400 and 4000 ug of glucan per dose (**Figure 5**). There was no significant body weight change in the treatment groups (after accounting for tumor growth) irrespective of dose of glucan or combination with antibody 3F8. At necropsy on day 21, there were no appreciable difference in the peripheral blood counts, cholesterol and blood chemistry between mice receiving different glucan doses. There was

also no difference in the histologic appearances of organs in mice treated with glucan at any of the dose levels, when compared to control mice that received saline.

By the oral route, only certain glucans, and frequent dosing were effective. For NMB7 tumors (**Figure 6**), 400 ug oral maitake was effective in synergizing with antibody 3F8, although late breakthroughs were seen. A 5 day/week po barley glucan regimen was equally as effective as the daily regimen. In contrast, a once a week or twice a week schedule of barley glucan was ineffective (data not shown). For the faster growing LAN1 tumors (**Figure 7**) unlike barley glucan (lot #1 and lot #2), po lentinan, PSK or mannan were all ineffective. The effect of Maitake glucan was not significantly different from glucan dose or 3F8 alone (**Figure 8**). Glucan from barley was more effective than that from oat despite similarities in their molecular sizes (**Figure 11**).

Barley glucans of large molecular weight is more effective In **Figure 9**, barley glucans of different molecular sizes (40K, 123K, 183K, 254K, 359K) were tested at an oral dose of 40 ug. Anti-tumor effect improved with increasing molecular weights, such that glucan of 359K size was most effective. Nevertheless, at high doses (e.g. 400 ug) even the less effective sizes, 40K and 128K showed some benefit (092900megazyme.xls from folder megazyme). Glucan derived from oat also showed syngergistic anti-tumor effect when administered in the presence of 3F8. Both molecular size and viscosity appeared to be important for this anti-tumor effect. For example barley glucan (327K, >100 cSt or 250K, 25 cSt) and oat glucan (69 cSt or 20-30 cSt) were highly effective in synergizing with MoAb, whereas barley glucan of 137K and 5.6 cSt was not (**Figure 10**).

Role of NK cells in glucan effect. Removal of NK cells using anti-Asialo GM1 antiserum eliminated a substantial amount, although not completely the anti-tumor activity of glucan (**Figure 11 and 12**). Moreover in beige mice glucan was effective in synergizing with 3F8 (data not shown), suggesting that at least part of the anti-tumor activity was mediated by NK-independent cytotoxicity.

IgG3-F(ab`)2 or IgG1 antibodies do not have substantial anti-tumor activity (Figure 13) The role of Fc in mediating the anti-tumor effect of glucan was apparent when Fc was removed by pepsin or when IgG1 isotype (data not shown) was used. Neither was able to activate complement or mediate efficient ADCC, and neither has significant anti-tumor effect when administered with 400 ug of oral glucan.

Barley Glucan synergizes with other complement fixing antibodies in a wide spectrum of human tumors. IgG3 anti-GD3 antibody R24 synergized with po glucan in shrinking ***melanoma SKMel-28*** xenografts (**Figure 14**). Rituximab (humanized IgG1 anti-CD20) synergized with po glucan in eradicating ***EBV-lymphoma***, **Daudi lymphoma, and Hodgkin's disease.** Although anti-EGF-R antibody 428 (mouse IgG2a) was able to suppress **epidermal carcinoma**[40] A431 tumor growth, 428 plus oral glucan was much more effective in eradicating tumors.

	Cell line	**Antibody**
Subcutaneous tumor models		
Human xenografts		
	NMB7	3F8
	LAN-1	3F8
	SK-N-ER	3F8
	SK-N-	3F8
	SKMel-28	R24
	EBV-lymphoma	Rituximab
	Daudi lymphoma	Rituximab
	Hodgkin's disease	Rituximab
	Epidermal Carcinoma 528	

Syngeneic tumors		
	EL4	3F8
	B16D14	3F8
	B16D14-Kb	3F8
	B16D14-Kb-Kd	3F8
Metastatic tumor models		
Human xenografts		
	Daudi	3F8
Syngeneic tumors		
	EL4	3F8

Glucan synergizes with 3F8 in C57Bl/6 mice against syngeneic tumors. While our early experiments were focused on human xenografts in athymic or SCID mice, similar synergism was observed in immunologically intact mice grafted with GD2-positive B16 melanomas (B16D14 [**Figure 15**], B16D14Kb, or B16D14KbKd [**Figure 16**]) or GD2-positive EL4 lymphoma [**Figure 18**]. Neither barley glucan nor 3F8 by itself showed anti-tumor effect. In contrast the combination of glucan and 3F8 was able to suppress almost entirely tumor growth in C57Bl/6 mice. In control B16 tumors which were GD2-negative, glucan plus 3F8 had no anti-tumor effect. We conclude that the glucan effect observed was not restricted to immune deficient animals. In addition, it requires tumor-specific antibodies, i.e. effective only if tumor cells carried the target antigen.

Glucan synergizes with 3F8 in C57Bl/6 mice against metastatic tumors. When EL4 lymphoma cells were injected iv, mice developed widespread tumors in their lungs, livers and at the site of injection and rapidly succumbed. Control animals were dead by 14 days following EL4 injection, while the group treated withi.v.3F8 plus 400 ug glucan po (treatment initiated 5 days following EL4 injection) had significantly longer survival.

Barley Glucan syngergizes with 3F8 in prolonging survival Nude mice (n=21) with established neuroblastoma NMB7

xenografts (0.7-0.8 cm diameter tumor at the beginning of treatment) were treated with 3F8 (200 ug twice a week iv) and 400 ug of barley β-glucan po daily for a total of 3 weeks. Control mice (n=21) received either saline alone, 3F8 alone, or β-glucan alone. Median survival was 30 days in control and >300 days in the treatment (3F8 plus β-glucan) group (p<0.001). Long-term survival was 56% in the treatment group and 5% in the control group (**Figure 19**). In nude mice bearing established LAN1 xenografts (also 0.7-0.8 cm diameter tumor at the beginning of treatment) median survival increased from 20 days in the control group (n=38) to 42 days in the 3F8 plus glucan group (n=48) (p<0.001, **Figure 20**).

Discussion

Using the human xenograft and syngeneic mouse tumor models, we have made the following observations. Glucan derived from barley or oats can synergize with monoclonal antibodies in suppressing or eradicating tumors, while β-glucan or antibody alone has little anti-tumor effect. Anti-tumor response requires antibodies that activate complement, whether mouse IgM, mouse IgG3 or human IgG1. Glucans of high molecular weight 250K and viscosity (20 cSt) possess this special effect. Oral route is at least equally (if not more) effective than the intraperitoneal route. It is a dose-dependent phenomenon, where 400 ug per dose is required for maximal effect. Natural killer cells are not essential for this glucan phenomenon, although they contribute to the anti-tumor effect. Normal T-cells and B-cells are not required for the anti-tumor effect since immune-deficient mouse strains demonstrate the glucan effect, whether athymic, SCID or SCID-beige mice are used. In addition, normal T-cells and B-cells do not interfere with this glucan effect, as shown in the syngeneic C57Bl/6 mouse model. Most importantly, oral glucan is well-tolerated by all the mice

tested so far, with no noticeable change in body weight, blood counts or organ histologies, even at doses as high as 4 mg per dose per day.

Our findings differ significantly from previous observations and predictions on the use of glucans in cancer treatment. In the past it was thought that the 1,3-1,6-βlinkage was absolutely required for the glucan anti-tumor effect.[17] This structure contains 1,3-β-D-glucopyranosyl units along which are randomly dispersed single β-D-glucopyranosyl units attached by 1,6- linkages, giving a comb-like structure (e.g. Lentinan, Schizophyllan, Laminarin, and glucan from Baker's yeast). In these models, it was believed that T-cells cells were activated and indeed required for the anti-tumor effect. In addition, it was believed that small molecular weight glucan should be more effective than high molecular weight glucan and that the most effective administration should be intravenous or intraperitoneal routes. Indeed, Betafectin (PGG) was derived from a genetically engineered Saccharomyces cerevisiae which makes 1,3-1,6-β-D glucans with weaker interchain associations.[24] It was manufactured fori.v.injection to improve macrophage function in the hope of reducing infectious complications and improving wound healing. Barley glucan is a linear polymer with 1,3 and 1,4 linkages; however, it is not a comb like structure. We did not find any anti-tumor effect of barley glucan when given alone. However, when used in combinations with monoclonal antibodies, the syngergistic effect was remarkable. In addition, glucans of high molecular weight and high viscosity appeared to be most effective, contrary to what one might expect for macromolecular transport. Although barley glucan activates granulocyte mediated ADCC in vitro (data not shown), the effects of glucan may be indirect. It is not clear if the absorption of glucan is necessary for its anti-tumor effect.

The exact mechanism of how barley glucan enhances the anti-tumor effect of monoclonal antibodies in vivo is unknown.

One possible mechanism of action may relate to innate receptors for β-glucan, in a hard-wired information network on phagocytes and lymphoid cells; receptors that normally recognize death signals and microbial molecular patterns.[25] Monoclonal antibodies, either through Fc interaction or through CR3 interaction with iC3b, direct cytotoxicity to tumor cells, a process greatly enhanced by β-glucan activation of effector cells. This killing is immediate, nonclonal, and obligatory, a process often referred to as innate immunity. The consequence of this innate effector arm is the activation of costimulatory molecules and induction of cytokines and chemokines that will enhance adaptive immunity to the tumor cells. Thus, activation of immunity is based upon discrimination between dangerous and nondangerous antigens; and if cancer can be viewed as constant danger to the immune system,[26,27] memory T-cells will not become tolerized. β-glucan receptors belong to a family of pattern recognition receptors (PRRs) specific for pathogen-associated molecular patterns (PAMPs). They are biosensors for invading pathogens widely distributed in vertebrate and invertebrate animals,[28] a nonclonal host defense pathway with structural and functional homologies in phylogenetic lineages that diverged over a billion years ago. A limited set of conserved signaling modules such as Toll/IL-1R homology domain, the SIIK domain, the Rel homology domain and perhaps the leucine rich regions (LRR) domain, represent the original building blocks for PRRs. For example, insects respond to infection by rapid and transient synthesis of antimicrobial peptides by the fat body and hemocytes. In drosophila antibacterial peptides (cecropin, attacin and definsin) and anti-fungal peptide drosomycin are dependent on the Toll pathway; this PRR

activates a proteolytic cascade to act on Spatzle, or 18-Wheeler (18W) to form the active ligand for Toll. Activation of the human Toll homologue results in induction of IL-1, IL-6, IL-8, B7.1 and B7.2. With B7, signaling through CD28 occurs; T-cell become activated followed by expression of surface molecules such as TNF-α and TNF-β, Fas ligand (L), CD40L, CD30L, and CD27L, as well as secretion of cytokines. Interestingly, for dendritic cells, when they express B7, they stop antigen uptake (i.e. becoming nonendocytic) and assume their antigen-presenting role. Certain activation motifs such as LRR are present in Toll and the endotoxin receptor CD14; they are also present intracellularly in plants, probably responsible for resistance to intracellular pathogens.[28]

Carbohydrate-rich antigens on bacteria or fungi can activate complement. Alternatively, specific antibodies can also deposit complement components on pathogens or cancer cells, such as the C3b fragment of C3, which is rapidly proteolyzed into iC3b fragment by serum factor I. These iC3b fragments can glue pathogens or tumor cells to the iC3b-receptors (CR3, CD11b/CD18) on phagocytic cells and NK cells, stimulating phagocytosis and/or cytotoxic degranulation. Thus, antibody and complement link innate and adaptive immunity by targeting antigens to different cells of the immune system, e.g. via CR3 and Fc for phagocytic cells, CR2 for B cells, and CR1, CR2, or CR3 for follicular dendritic cells.[29] For neutrophils, CR3-dependent phagocytosis requires ligation of two distinct binding sites, one for iC3b and a second site for β-glucan. Without β-glucan, iC3b-opsonized target cells are resistant to killing.[30] Microbes possess polysaccharides that can activate the lectin domain on CR3, leading to phagocytosis and cytotoxic degranulation. In contrast, human cells (including tumors) lack these CR3-binding polyscharides, thus the inability of CR3 to mediate

phagocytosis or extracellular cytotoxicity of tumor cells opsonized with iC3b. The lectin site of CR3 can also influence transmembrane signaling of endogenous neutrophil membrane GPI-anchored glycoproteins (CD14, CD16, CD59, CD87[uPAR]). In a mouse mammary tumor model, where there is naturally occurring IgM and IgG antibodies, injection of yeast soluble β-glucan could suppress tumor growth, an effect lost in C3-deficient or CD11b (CR3)-deficient mice.[31,32] Since iC3b bound to a primary protein antigen can also enhance recognition and specific antibody synthesis by antigen-specific B cells,[33] the presence of glucan plus complement activation may enhance B-cell response to pathogens or tumor cells.

If this syngergistic effect of β-glucan on antibodies is active in humans, our findings may have broad clinical implications. First the efficacy of monoclonal antibodies in cancer (e.g. Herceptin, Rituximab, Dacluzimab, anti-GD2 and anti-EGF-R MoAb) can be potentially enhanced.[34] Nevertheless, even though toxicity from glucan is expected to be minimal, the enhanced efficacy of MoAb may also increase MoAb-mediated toxicity. For example, the side effects of Herceptin on cardiac function, or anti-GD2 MoAb on neuropathic pain may be increased. Second, since the amount and quality of barley and oat glucan in daily food intake can vary, future interpretations of efficacy trials using MoAb may need to take this into account, for both preclinical and clinical studies. Indeed since glucan synergizes equally well with IgM antibody, the presence of natural IgM anti-tumor and anti-viral antibodies can be a confounding factor in interpreting in vivo tumor response, whether in preclinical models or in clinical trials, unless the po intake of glucan in mouse chow is standardized. Most importantly, since many carbohydrate tumor vaccines (e.g. GM2-KLH,[35] GD2-KLH, MUC-1,[36] and globo-H-hexasaccharide[37])

induce primarily specific IgM response, glucan may enhance their anti-tumor effects. If this glucan effect can be generalized to other antibody-mediated host defense mechanisms, its role in infectious disease may also be intriguing. Serotherapy of certain drug resistant bacteria,[38] or viral (e.g. CMV) and fungal (e.g. cryptococcus and candida[39]) infections using antibodies may be enhanced by concurrent intake of β-glucan. One can speculate if the function of pre-existing protective antibodies, e.g. towards tetanus or streptococcus, can be enhanced by oral β-glucan; indeed, if it can enhance the protective effects of common bacterial vaccines. The successful treatment of Alzheimer's disease using antibodies specific for amyloid β-peptide in the mouse model is a provocative finding[44]; it is likely that β-glucan may enhance the antibody effect. When one consider glucan-effect in the context of auto-immune disease, it is also plausible that tissue injury may be increased by oral glucan, leading to exacerbations of such diseases as rheumatoid arthritis. It is possible in those auto-immune diseases in which auto-antibodies cause tissue damage, clinical signs and symptoms may be modulated by oral intake of glucan. In view of these potential beneficial and adverse effects of barley glucan on human diseases, a better understanding of their immune effects seems highly worthwhile.

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Second Series of Experiments

Purpose: In vitro β-glucan can enhance tumor cytotoxicity through iC3b receptors on leukocytes. We test if (1→3),(1→4)-β-D-glucan (β-glucan) can synergize with anti-GD2 monoclonal antibody (MoAb) 3F8 (mouse IgG3) in therapy of human neuroblastoma xenografts.

Experimental Design: Athymic nude mice with established neuroblastoma xenografts were treated with daily intraperitoneal or oral β-glucan, in the presence/absence of intravneous MoAb twice a week, for 22-29 days. Serial tumor volumes and body weights were monitored.

Results: 3F8 plus β-glucan produced near-complete tumor regression/disease stabilization, while 3F8 or β-glucan alone did not significantly affect tumor growth. For NMB7 tumors, median survival of 3F8 plus β-glucan group was 5.5 fold that of control groups ($p<0.001$), and for LAN-1 the survival difference was 2.6 fold. 47% of the mice with NMB7 and 18% with LAN-1 remained progression-free in contrast to <3% of controls. Antitumor effect was seen at ∃40 ug glucan dose,i.v.or po, and in all human neuroblastoma cell lines tested. No toxicities were noted in mice treated with either β-glucan alone or 3F8 plus β-glucan (4 to 4000 ug per dose). In contrast to anti-GD2 MoAb 3G6 (IgM), 3F8 F(ab`)$_2$ and MoAb 8H9 (IgG1) did not activate complement and had no synergy with β-glucan. Anti-tumor effect of 3F8 plus oral β-glucan persisted after anti-asialo-GM1 antibody treatment, as well as in NK-deficient host.

Conclusions: Oral 1,3-1,4-β-glucan synergized with anti-tumor IgG and IgM MoAb in vivo. Since β-glucan was well tolerated and inexpensive, its potential value in cancer therapy deserves further investigation.

INTRODUCTION

Monoclonal antibodies (MoAb) selective for tumors have therapeutic potential (1). The introduction of hybridoma technology by Kohler and Milstein in 1975 (2) and advances in molecular biologic techniques have greatly expanded the potential of MoAb in human cancers. Evidence of efficacy in clinical trials is increasingly evident: 17-1A in colon cancers (3), anti-CD20 in lymphoma (4, 5), anti-HER2 antibodies in breast cancer (6, 7), and M195 against CD33 in acute leukemia (8) are good examples. Our laboratory has developed the MoAb 3F8 which targets the ganglioside GD2 overexpressed on neuroblastoma. 3F8 has been shown to have high specificity and sensitivity in the radioimmunodetection of minimal residual disease in patients with NB (9), and a significant clinical impact when used as adjuvant therapy (10).

The immune basis of clinical tumor response to MoAb is at least two-fold, direct cytotoxicity and induced immunity. Antibody dependent cell-mediated cytotoxicity (ADCC) and complement mediated cytotoxicity (CMC) are responsible for the direct killing of tumor cells. On the other hand, through tumor opsonization (11) or idiotype network (12), tumor-specific immunity is induced. β-glucans are polymers of glucose extractable from cereals, mushrooms, seaweed and yeasts (13). They are (1→3)-β-D-glucopyranosyl polymers with randomly dispersed single β-D-glucopyranosyl units attached by (1→6)- linkages, giving a comb-like structure. The (1→3)-β backbone and the (1→6)-linked branches were thought to be important for their immune effects. Lentinan (from Lentinus edodes, Basidiomycete family) is a high molecular weight (MW) β-glucan with (1→6) branches off every three (1→3)-β-D-glucopyranosyl residues and it has been licensed in Japan for cancer treatment. Schizophyllan (from Schizophyllum commune, Basidiomycete family) and β-glucan

from Baker's yeast (Saccharomyces cerevisiae) have similar structures. Laminarin (from seaweed), a small MW β-glucan, has (1→6)-β branches occurring at every ten (1→3)-β-D glucopyranosyl units. On the other hand, β-glucan from barley, oat or wheat has mixed (1→3) and (1→4)-β-linkage in the backbone, but no (1→6)-β branches and are generally of high MW. Although barley (1→3),(1→4)-β-D-glucan has been shown in vitro to bind to CR3 (14), activate ADCC mediated by natural killer cells (15-17), monocytes (18, 19), and neutrophils (17, 19), as well as stimulating tumor necrosis factor (TNFα) production by monocytes (20), their in vivo immunomodulatory effects in cancer models have yet to be investigated.

We now report our findings that oral (1→3),(1→4)-β-D-glucan derived from barley or oats can greatly enhance the activity of anti-tumor monoclonal antibodies in xenograft models. Because β-glucan is nontoxic, well tolerated and inexpensive, its role in cancer therapy deserves careful study.

MATERIALS AND METHODS

Cell lines Human neuroblastoma cell lines LAN-1 were provided by Dr. Robert Seeger, Children's Hospital of Los Angeles, Los Angeles, CA, and NMB7 by Dr. Shuen-Kuei Liao (McMaster University, Ontario, Canada). Neuroblastoma cell lines SK-N-JD, SK-N-ER, and SK-N-MM were established from patients with metastatic disease treated at Memorial Sloan-Kettering Cancer Center (MSKCC), New York, NY. Cell lines were cultured in 10% defined calf serum (Hyclone, Logan, UT) in RPMI with 2 mM L-glutamine, 100 U/ml of penicillin (Sigma, St. Louis, MO), 100 ug/ml of streptomycin (Sigma), 5% CO_2 in a 37°C humidified incubator. Normal human mononuclear cells were prepared from heparinized bone marrow

samples by centrifugation across a Ficoll density separation gradient.

Antibodies Monoclonal antibodies 3F8 (mouse IgG3), 3G6 (mouse IgM), and 8H9 (mouse IgG1) reactive with neuroblastoma have been previously described (21, 22). They were produced as ascites and purified by affinity chromatography: protein A (Pharmacia, Piscataway, NJ) for 3F8 (21), protein G (Pharmacia) for 8H9 (22), and C1q-sepharose (Pierce, Rockford, IL) for 3G6 (21, 23). These antibodies were >90% pure by SDS-PAGE. $F(ab`)_2$ fragments were prepared by pepsin digestion as previously reported (24). TIB114 (N.S.7), a hybridoma secreting an IgG3 control antibody, was obtained from American Type Culture Collection (ATCC). Rabbit anti-asialo-GM1 antibody (Wako Pure Chemical Industries, Osaka, Japan) diluted to 1 mg/ml of protein was administered at 200 ul ip on days 0, 1, 2, 7, 14, 21.

Glucan (1→3),(1→4)-β-D-glucan derived from barley and (1→4)-β-D-mannan were purchased from Sigma. Sugar composition and linkage analysis were performed by the Complex Carbohydrate Research Center, University of Georgia, Athens, Georgia, supported in part by the Department of Energy-funded Center for Plant and Microbial Complex Carbohydrates (DF-FG09-93ER-20097). Barley glucan was dissolved by boiling for 10 minutes in normal saline.

Mice and treatment Athymic Balb/c mice were purchased from NCI, Frederick, MD, and CB-17 SCID-Beige mice from Taconic (Germantown, NY). Tumor cells were planted (1-5 $x10^6$ cells) in 100ul of Matrigel (BD BioSciences, Bedford, MA) subcutaneously. Following implantation, tumor sizes (maximum width and lengths) were measured. Tumor size was calculated as product of the 2 perpendicular diameters. Treatment studies started in groups of 4-5 mice per cage

when tumor diameter reached 0.7 to 0.8 cm, usually by 14-21 days of tumor implantation. Mice received antibody treatment intravenously (generally 200 ug per dose by retroorbital injection) twice weekly and β-glucan by intragastric gavage (generally 400 ug per dose) every day for 3 weeks (22-days of β-glucan and 6-doses of antibody). Mice were weighed once a week and tumor size measured twice a week. Mice were sacrificed when tumors reached sizes that interfered with their well-being.

Assays for soluble cytokines Sera from mice were obtained 1 h, 4 h, 8 h, 24 h, 48 h, and 72 h after oral β-glucan. They were assayed for soluble cytokine IL-12 (p70) and TNFα, all reagents from Endogen (Woburn, MA). Briefly, 96-well microtiter plates were coated with either monoclonal anti-mouse IL12 at 5 ug/ml or monoclonal anti-TNFα at 0.8 ug/ml overnight at ambient temperature. The mouse IL12 standard ranged from 1000 pg/ml in 1:3 serial dilutions and the TNFα standard ranged from 490 pg/ml in 1:2 serial dilution. Test samples (serum diluted 1:2) were added to the plates and incubated for 2 hours at ambient temperature. The detecting antibody, biotinylated anti-mouse IL12 monoclonal at 1:100 dilution for the IL12 assay, or biotinylated anti-mouse TNFα monoclonal at (1:50) for the TNFα ELISA was added. The plates were incubated at ambient temperature for one hour. After PBS wash, the secondary antibody, which was HRP-conjugated streptavidin at 1:400 for IL12, and 1:200 for TNFα, was added to the plates for a 30 min incubation at ambient temperature. After another wash, tetramethylbenzidine was added as the substrate for the color reaction for 30 min, and absorbance was read at 450 nm using an ELISA plate reader. The limits of detection were 12 pg/ml for the mouse IL12 ELISA, and 10 pg/ml for the mouse TNFα ELISA.

Immunostaining for tumor vasculature LAN-1 xenografts were removed 1h, 4h, 8h, 16h, 24h, 48h, 96h and 216 h after treatment. Tumor vasculature was assayed by immunostaining with an anti-blood vessel antibody. Eight mm cryostat frozen tumor sections were fixed in acetone and washed in PBS. Endogenous peroxidases were blocked in 0.3% H_2O_2 in PBS. Sections were incubated in 3% bovine serum albumin containing 0.25% gelatin for 60 minutes, after the avid-biotin blocking step. Incubation with the biotinylated rat anti-murine PECAM IgG2a MoAb, MEC13.3 (1 mg/ml) (BD PharMingen, SanDiego, CA) was carried out at room temperature for 60 minutes followed by ABC complex (Vector Laboratories, Burlingame, CA). Color was developed with DAB peroxidase substrate kit (Vector). A 10% hematoxylin counterstain for 4 minutes was used.

Statistical analysis Average tumor size over time between groups was compared. The null hypothesis was no difference in size over time. To test the hypothesis, the square of size differences summed over time was used, which in effect compared the trajectories of the average tumor sizes between treatment groups.

$$SS\_DEV = \sum_{i=1}^{k} (x_i - y_i)^2$$

where there were k time points and x_i and y_i were the average tumor sizes at time i for each treatment group.

RESULTS

Synergy between barley β-glucan and anti-GD2 antibody 3F8 in eradicating human neuroblastoma. 3F8 is a murine IgG3 monoclonal antibody that activates mouse and human complement, and mediates effective ADCC against human neuroblastoma cells in vitro. β-glucan when administered

orally at 400 ug per day had no appreciable effect on NMB7 tumor growth as did antibody 3F8 giveni.v.alone. However, when β-glucan and 3F8 were used in combination, tumor growth was near totally suppressed. In >47% of mice, tumors remained permanently suppressed following treatment. Similar observations were made with neuroblastoma cell lines derived from different sources: LAN-1 (**Figure 1a**), NMB7 (**Figure 1b**) SK-N-ER (**Figure 1c**), SK-N-MM and SK-N-JD (data not shown). β-glucan was equally effective when administered orally or intraperitoneally. In contrast, for the GD2-negative rhabdomyosarcoma, HTB82, 3F8 plus β-glucan treatment was ineffective (data not shown). In addition, TIB114 (IgG3 control) plus barley β-glucan, or 3F8 plus mannan had no anti-tumor (data not shown). When 3F8 dose was decreased from 200 ug to 40 ug, the anti-tumor effect was lost (data not shown). There was no detectable serum IL-12 or TNF-α release following oral β-glucan administration (data not shown). There was no immunohistochemically detectable effect of β-glucan on tumor vessel formation (data not shown).

Dose response curve for ip β-glucan. When the dose of intraperitoneal β-glucan was decreased by 10-fold from 4000 ug, it was clear that 4 ug was no longer effective in synergizing with MoAb 3F8 in suppressing NMB7 growth. Interestingly, both ip and oral 1,3-1,4-β-glucan (at 400 ug per day) were effective (**Figure 2**).

Oral β-glucan versus ip β-glucan. When oral β-glucan was studied in NMB7 tumors (**Figure 3**), similar dose response was found. While an oral dose of 400 ug was curative for some tumors, breakthroughs were seen for lower dose levels, with those receiving 4 ug escaping sooner those receiving 40 ug. Using the LAN-1 tumor model, neither 4 nor 40 ug β-glucan were effective (data not shown). There was no significant

body weight change in any of the treatment groups (after accounting for tumor weight), irrespective of β-glucan dose or co-administration with 3F8. At necropsy on day 22, there were no appreciable differences in the peripheral blood counts, cholesterol and blood chemistry between mice receiving different β-glucan doses. There was also no difference in the histologic appearances of organs in mice treated with β-glucan at any of the dose levels, when compared to control mice that received saline.

By the oral route, daily β-glucan schedule was necessary. A 5 day/week po β-glucan regimen was comparable to the daily regimen. In contrast, a once a week or twice a week schedule of β-glucan had no anti-tumor effect (data not shown).

Role of NK cells in β-glucan effect. Removal of NK cells by anti-Asialo GM1 antiserum eliminated a substantial amount, although not completely the anti-tumor activity of β-glucan (**Figure 4**). Moreover, in SCID-beige mice which lack NK cells, β-glucan was still effective in synergizing with 3F8 (data not shown), suggesting that at least part of the anti-tumor activity was mediated by NK-independent cytotoxicity.

IgG3-F(ab`)$_2$ or IgG1 antibodies did not have anti-tumor activity. The role of Fc in mediating the anti-tumor effect of β-glucan was apparent when Fc was removed by pepsin or when IgG1 isotype MoAb 8H9 was used (data not shown). Neither was able to activate complement or mediate efficient ADCC, and neither has significant anti-tumor effect when administered with 400 ug of oral β-glucan.

Synergy of β-Glucan with 3F8 in prolonging survival. Nude mice (n=22) with established neuroblastoma NMB7 xenografts (0.7-0.8 cm diameter tumor at the beginning of treatment)

were treated with 3F8 (200 ug twice a week iv) and 400 ug of β-glucan po daily for a total of 3 weeks. Control mice received either saline alone (n=10), 3F8 alone (n=8), or β-glucan (n=16) alone. Median survival was 30 days in control groups and 166 days in the treatment (3F8 plus β-glucan, n=22) group (p<0.001). Long-term survival was estimated at 47% in the treatment group and 3% in the control group (saline alone, 3F8 alone, or β-glucan alone) (**Figure 5**). Similar experiments were carried out in nude mice bearing established LAN-1 xenografts (also 0.7-0.8 cm diameter tumor at the beginning of treatment). Among control mice treated with either saline alone (n=31), 3F8 alone (n=16), or β-glucan (n=8) alone, tumor growth was rapid. Median survival was 21 days in control groups (n=55) and 54 days in the treatment (3F8 plus β-glucan) group (n=82) (p<0.001, **Figure 6**). Long-term survival was estimated at 18% in the treatment group and 0% in the controls.

DISCUSSION

Using the human xenograft models, we have made the following observations. β-Glucan derived from barley can synergize with monoclonal antibodies to suppress and/or eradicate tumors, while β-glucan or antibody alone has little anti-tumor effect. Anti-tumor response requires antibodies that activate complement, and both mouse IgM and mouse IgG3 were effective. Oral administration of β-glucan is at least equally (if not more) effective than the intraperitoneal route. It is a dose-dependent phenomenon, where ≥400 ug per dose is required for maximal effect. Natural killer cells are not essential for this β-glucan phenomenon, although they contribute to the anti-tumor effect. Normal T-cells and B-cells are not required for the anti-tumor effect since immune-deficient mouse strains demonstrate the β-glucan effect, in both athymic and SCID-beige mice. Most importantly, oral β-glucan is well-tolerated by all the mice

tested so far, with no noticeable change in body weight, blood counts or organ histologies, even at doses as high as 4 mg per dose per day.

Our findings differ significantly from previous observations and predictions on the use of β-glucans in cancer treatment. In the past it was thought that the (1→3), (1→6)-β linkage was absolutely required for the β-glucan anti-tumor effect (13). This structure contains (1→3)-β-D-glucopyranosyl units along which are randomly dispersed single β-D-glucopyranosyl units attached by (1→6)- linkages, giving a comb-like structure (e.g. Lentinan, Schizophyllan, Laminarin, and glucan from Baker's yeast). In these models, it was believed that T-cells were activated and indeed required for the anti-tumor effect. In addition, it was believed that small molecular weight β-glucan should be more effective than high molecular weight β-glucan and that the most effective administration should be intravenous or intraperitoneal routes. Indeed, Betafectin was derived from a genetically engineered Saccharomyces cerevisiae which makes (1→3),(1→4)-β-D-glucans with weaker interchain associations (25). It was manufactured fori.v.injection to improve macrophage function in the hope of reducing infectious complications and improving wound healing. Barley β-glucan is a linear polymer with (1→3)-β and (1→4)-β linkages; however, it is not a comb like structure. We did not find any anti-tumor effect of barley β-glucan when given alone. However, when used in combinations with monoclonal antibodies, the synergistic effect was remarkable. Although β-glucan activates granulocyte mediated ADCC in vitro (data not shown), the effects of β-glucan may be indirect. It is not clear if the absorption of β-glucan is necessary for its anti-tumor effect. The exact mechanism of how β-glucan enhances the anti-tumor effect of monoclonal antibodies in vivo is unknown.

Monoclonal antibodies, either through Fc interaction or through CR3 interaction with iC3b, target cytotoxicity to tumor cells, a process greatly enhanced by β-glucan activation of effector cells. β-glucan activates leukocytes by binding to CR3 or to β-glucan receptors (26). After antibodies deposit complement components on pathogens or cancer cells, C3b is rapidly proteolyzed into iC3b fragment by serum factor I. These iC3b fragments then opsonize the pathogens or tumor cells for the iC3b-receptors (CR3, CD11b/CD18) on phagocytic cells and NK cells, stimulating phagocytosis and/or cytotoxic degranulation. Thus, antibody and complement link innate and adaptive immunity by targeting antigens to different cells of the immune system, e.g. via CR3 and Fc for phagocytic cells, CR2 for B cells, and CR1, CR2, or CR3 for follicular dendritic cells (27). For neutrophils, CR3-dependent phagocytosis requires ligation of two distinct binding sites, one for iC3b and a second site for β-glucan. Without β-glucan, iC3b-opsonized target cells are resistant to killing (17). Microbes possess polysaccharides that can activate the lectin domain on CR3, leading to phagocytosis and cytotoxic degranulation. In contrast, human cells (including tumors) lack these CR3-binding polysaccharides, thus the inability of CR3 to mediate phagocytosis or extracellular cytotoxicity of tumor cells opsonized with iC3b. The lectin site of CR3 can also influence transmembrane signaling of endogenous neutrophil membrane GPI-anchored glycoproteins (e.g. CD14, CD16, and CD59). In a mouse mammary tumor model, where there are naturally occurring IgM and IgG antibodies, injection of yeast soluble β-glucan could suppress tumor growth, an effect lost in C3-deficient or CD11b (CR3)-deficient mice (28, 29). Since iC3b bound to a primary protein antigen can also enhance recognition and specific antibody synthesis by antigen-specific B cells (30), the

presence of β-glucan plus complement activation may enhance B-cell response to pathogens or tumor cells.

Another mechanism of action of β-glucan may relate to innate receptors for β-glucan, in a hard-wired information network on phagocytes and lymphoid cells; receptors that normally recognize death signals and microbial molecular patterns (31). These innate receptors are biosensors for invading pathogens widely distributed in vertebrate and invertebrate animals (32), a nonclonal host defense pathway with structural and functional homologies in phylogenetic lineages that diverged over a billion years ago. Following β-glucan activation of leukocytes, killing is immediate, nonclonal, and obligatory, a process often referred to as innate immunity. The consequence of this innate effector arm is the activation of costimulatory molecules and induction of cytokines and chemokines that will enhance adaptive immunity to the tumor cells. (33, 34). Thus, antibodies, complement, phagocytes, and "danger" receptors form core elements of innate immunity while antigen-presenting cells, T and B lymphocytes constitute essential players in acquired immunity.

Despite the availability of tumor-selective monoclonal antibodies and the ample supply of phagocytes/natural killers, shrinkage of established tumors following antibody treatment alone, and the acquisition of specific immunity, are not common in both preclinical models and cancer patients. The absence of a danger signal and the diminution of complement action by complement resistance proteins on tumor cells may explain the inefficiency of antibody mediated clinical responses (35). Lipopolysaccharide and β-glucan, being cell wall components of bacteria and fungus, respectively, are potent danger signals to the immune systems in all life-forms, from Drosophila to man (36).

While LPS is too toxic for human use, β-glucan is relatively benign. If this synergistic effect of β-glucan on antibodies is active in humans, our findings may have broad clinical implications. First the efficacy of monoclonal antibodies in cancer (e.g. Herceptin, Rituximab, Dacluzimab, anti-GD2 and anti-EGF-R MoAb) can be potentially enhanced (37). Nevertheless, even though toxicity from β-glucan is expected to be minimal, the enhanced efficacy of MoAb may also increase MoAb-mediated toxicity. For example, the side effects of Herceptin on cardiac function, or anti-GD2 MoAb on neuropathic pain may be increased. Second, since the amount and quality of barley and oat glucan in daily food intake can vary, future interpretations of efficacy trials using MoAb may need to take this into account, for both preclinical and clinical studies. Indeed since glucan synergizes equally well with IgM antibody, the presence of natural IgM anti-tumor and anti-viral antibodies can be a confounding factor in the interpretation of in vivo tumor response, whether in preclinical models or in clinical trials, unless the oral intake of glucan in mouse chow is standardized. Most importantly, since many carbohydrate tumor vaccines (e.g. GM2-KLH (38), GD2-KLH, and globo-H-hexasaccharide (39)) primarily induce specific IgM response, glucan may enhance their anti-tumor effects. In view of these potential beneficial effects of barley glucan on cancer therapy, a better understanding of their immune effects seems highly worthwhile.

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Third Series of Experiments

Background: β-glucan primes leukocyte CR3 for enhanced cytotoxicity and synergizes with anti-tumor monoclonal antibodies (MoAb). We studied (1→3)-β-D-glucans in xenograft tumor models, and examined the relationship of its anti-tumor effect and physico-chemical properties.

Methods: Established subcutaneous human xenografts were treated with β-glucan daily and MoAb twice weekly by intragastric injection for 29 days. Control mice received either MoAb alone or β-glucan alone. Tumor sizes were monitored over time. β-glucans were studied by carbohydrate linkage analysis, and high performance size-exclusion chromatography with multiple angle laser scattering detection.

Results: Orally administered β-D-glucan greatly enhanced the anti-tumor effects of MoAb against established tumors in mice. This effect correlated with the molecular size of the (1→3),(1→4)-β-D-glucan. (1→3), (1→6)-β-D-glucans also synergized with MoAb, although the effect was generally less. We observed this β-glucan effect irrespective of antigen (GD2, GD3, CD20, epidermal growth factor-receptor, HER-2), human tumor type (neuroblastoma, melanoma, lymphoma, epidermoid carcinoma and breast carcinoma) or tumor sites (subcutaneous *versus* systemic).

Conclusion: Given the favorable efficacy and toxicity profile of oral β-D-glucan, its role in cancer treatment as an enhancer of the effect of MoAb therapy deserves careful study.

Introduction

Evidence of efficacy of monoclonal antibodies (MoAb) against human cancer in clinical trials is increasingly evident.

However, induced or administered antibodies to human tumors have not realized their fullest therapeutic potential, even when they can activate complement-dependent cytotoxicity (CDC) and antibody-dependent cell-mediated cytotoxicity (ADCC). The deposition of C3b and iC3b on tumor cells fails to stimulate phagocytosis or extracellular cytotoxicity by C3-receptor-bearing neutrophils, macrophages, and NK cells, even though these same effector cells can efficiently kill C3b and iC3b opsonized microorganisms. The receptor for iC3b, CR3 (also called CD11b/CD18, Mac-1, or αMβ2-integrin), is found in monocytes/macrophages, NK cells, and immune cytotoxic T-lymphocytes. CR3 activation requires the engagement of two sites on its α-subunit (CD11b): the iC3b-binding site within the I-domain at the N-terminus and a lectin site at the C-terminus (*1,2*). β-glucans are specific for the lectin site. When coated with iC3b, yeast cells (with their β-glucan-containing cell wall), engage both iC3b and lectin binding sites on leukocytes, triggering phagocytosis and respiratory burst (*2,3*). In contrast, tumor cells coated with iC3b cannot activate leukocytes because they lack the CR3-binding β-glucan (*4-7*). Soluble forms of β-glucans can bind to the lectin site (*8,9*) and prime both phagocytic and NK cells to kill iC3b coated tumor targets (*4,9,10*). In murine mammary tumor models in which iC3b was found, intravenous yeast β-glucan reduced tumor size by 70-95% (*11*). The loss of tumor response in the absence of complement-fixing IgM anti-tumor antibodies (SCID mice), or of C3 (C3 knockout mice), or of leukocyte CR3 (CR3 knockout mice) highlighted the critical components of this iC3b strategy (*11*).

Although (1→3)-β-D-glucans can be purified from yeast, seaweed and mushrooms, an inexpensive, convenient and safe source of pure (1→3),(1→4)-β-D-glucan is available from barley. Barley β-glucan has been shown to bind to CR3 in

vitro (*9*), to activate ADCC mediated by NK cells (*4,10,12*), monocyte (*8,13*), and neutrophils (*8,14*), as well as to stimulate TNF production by monocytes(*15*). However, its in vivo immunomodulatory effects, especially when administered by the oral route, have not been tested. In this study we report an unusually strong synergism between anti-tumor antibodies and intragastric injection of β-glucan against a broad spectrum of human tumor xenografts. We also undertake a preliminary investigation of molecular size requirements for this anti-tumor synergy with MoAb.

Methods

Cell lines The cell lines Daudi, RMPI 6666, HS455, SKMel-28 and A431 were from American Type Culture Collection (ATCC), Rockville, MD. LAN-1 was provided by Dr. R. Seeger, Children's Hospital of Los Angeles, Los Angeles, CA; NMB7 by Dr. S.K. Liao (McMaster University, Ontario, Canada); human breast carcinoma cell line BT474 was kindly provided by Dr. David Solit of Memorial Sloan-Kettering Cancer Center (MSKCC), New York, NY; SKNJD and SKNER were established at MSKCC. BT474 was cultured in Dulbecco's modified Eagle with Nutrient Mixture F12 (DMEM/F-12) (Life Technologies Inc. GIBCO-BRL, Rockville , MD) in a 1:1 mixture fortified with 10% newborn calf serum (Hyclone, Logan, UT), MEM non-essential amino acids (Gibco-BRL, Grand Island, NY), 100 U/ml of penicillin (Sigma, St. Louis, Mo), and 100 ug/ml of streptomycin (Sigma). All other cell lines were cultured in RPMI 1640 (Life Technologies Inc.) containing 10% defined calf serum (Hyclone) and 100U/ml of penicillin, 100 ug/ml of streptomycin and 2 mM L-glutamine (Sigma).

Antibodies MoAb 3F8 (mouse IgG3) and 3G6 (mouse IgM) reactive against GD2 ganglioside expressed on neuroectodermal tumors, and MoAb 8H9 (mouse IgG1) reactive with a glycoprotein expressed on these same tumors have been

previously described (*16,17*). They were purified to >90% purity by affinity chromatography: protein A (Pharmacia, Piscataway, NJ) for 3F8, and protein G (Pharmacia) for 8H9. Anti-GD3 antibody (R24) (*18*) was provided by Dr. P. Chapman of MSKCC. Hybridomas producing the anti-epidermal growth factor receptor (EGF-R) antibodies 528 (IgG2a) and 455 (IgG1) were obtained from ATCC (*19*). Rituximab (anti-CD20) and Herceptin (anti-HER2) were purchased from Genentech, San Francisco, CA.

β-Glucan Barley, oat and lichenan β-D-glucans were purchased from Sigma and Megazyme International Ireland Ltd., Wicklow, Ireland. Wheat β-glucan was kindly provided by Dr. P. Wood of Agriculture and Agri-Food Canada, West Guelph, Ontario. Betatrim (Quaker Oatrim, 5% β-glucan from oat) was provided by Rhodia Food, Cranbury, NJ. Laminarin was purchased from Sigma and from TCI America, Portland, OR. Lentinan (β-glucan extracted from the mushroom Lentinus edodes) was provided by the Drug Synthesis and Chemistry Branch, Developmental Therapeutics Program, Division of Cancer Treatment and Diagnosis, National Cancer Institute, Bethesda, MD. β-glucan was dissolved by boiling for 10 minutes in normal saline; Lentinan was dissolved first in DMSO before diluting in water. Digestion with lichenase (endo-1,3:1,4-β-D-glucanase) from B. subtilis (Megazyme), was carried out in sodium phosphate buffer (20 mM, pH 6.5) at 40°C for 10 minutes. Sugar composition and linkage analysis by gas chromatography-mass spectrometry following methylation was performed by the Complex Carbohydrate Research Center, University of Georgia, Athens, GA, supported in part by the Department of Energy-funded Center for Plant and Microbial Complex Carbohydrates (DF-FG09-93ER-20097) (*20*). The average ratio of (1→3) to (1→4)-β-linkage in (1→3),(1→4)-β-D-glucans derived from barley, oat and wheat was around 3:7. For molecular size and shape estimations, β-glucan was analyzed by size-exclusion

chromatography plus multiple-angle laser light scattering (MALLS) as previously described (*21,22*). Besides measuring molecular size by MALLS, the slope derived from root mean square radius versus molar-mass plots gave an estimate of the molecular shape: a slope of 0.33 being the shape of a sphere, 0.5 being random coils and 1.0 being rigid rods. High MW β-glucans were found to be random coils in contrast to low MW species which were more sphere-like.

Mice and treatment Athymic nu/nu mice were purchased from the National Cancer Institute-Frederick Cancer Center (Bethesda, Maryland) and ICR/SCID from Taconic (White Plains, NY) and maintained in ventilated cages. Experiments were carried out under Institutional Animal Care and Use Committee (IACUC) approved protocols, and institutional guidelines for the proper and humane use of animals in research were followed. Tumor cells were planted (1-5 $x10^6$ cells) in 100 μl of Matrigel (Sigma) subcutaneously. Tumor dimensions were measured two to three times a week with vernier calipers, and tumor size was calculated as the product of the two largest perpendicular diameters. For breast carcinoma xenograft studies, 6-8 week old female nude mice (NCI) were initially implanted with 0.72 mg 90-day release 17ß-estradiol pellet (Innovative Research of America, Sarasota, FL) subcutaneously into the right flank. Twenty-four hours later, 10^7 BT474 cells were implanted subcutaneously into the left flank. All treatment studies started in groups of 4-5 mice when tumor diameters reached 0.7 to 0.8 cm. Mice received antibody treatment (40-200 ug per day) i.v. (by retroorbital injection) twice weekly and oral β-glucan (400 ug per day) by intragastric injection every day for a total 4 weeks. Mice were weighed once a week and sacrificed according to IACUC guidelines. In the SCID mouse systemic human lymphoma (Daudi) model, 5

million cells were administered i.v., and treatment started 10 days later.

Statistical analysis Because measurement times varied between experiments, and mice in control groups frequently were sacrificed [as required by IACUC for rapidly enlarging tumors] before the end of each experiment, tumor growth was calculated by fitting a regression slope for each individual mouse to log transformed values of tumor size. Slopes were compared between groups using linear regression with monoclonal antibody treatment, β-glucan treatment and combination treatment as covariates. In the study of melanoma tumor growth, β-glucan was given at two different doses. Thus, dose was added as a covariate for analysis. In the study of epidermoid tumor growth, monoclonal antibody was given at three different doses and antibody dose was added as a covariate. Trends for slope by molecular weight were tested by linear regression of slope scores. Survival analysis was conducted by Cox regression using the indicator variables: monoclonal antibody treatment, β-glucan treatment, and combination treatment; in the survival study of lymphoma, Rituximab was given at two different doses and so dose of antibody was added as a covariate for analysis. All analysis were conducted using STATA (Stata Corporation, College Station, TX).

Results

Synergy between MoAb and barley β-glucan. We chose the mouse model because of its relative inefficiency in CDC and ADCC (23), and MoAb alone were typically ineffective against established tumors. Oral administration of β-glucan (average MW 210 kD) from barley alone at 400 ug qd x 29 days or antibody 3F8 i.v. alone had no appreciable effect on neuroblastoma LAN-1 tumor growth. The tumor growth rates for the β-glucan alone, 3F8 alone, and saline controls were virtually identical. In contrast, when we combined oral

β-glucan with i.v. 3F8, significantly less tumor growth was observed in the 3F8 antibody alone group, 0.7% vs 5.4% increase in tumor size per day, respectively. In the regression model, only combination treatment significantly reduced tumor growth (4.9% per day, 95% CI 2.4%, 7.4%, p= 0.001). Nude mice (n=22) with established NMB7 xenografts were treated with 3F8 (200 ug twice a week iv) and 400 ug of β-glucan po daily for a total of 4 weeks. Control mice received either saline alone, 3F8 alone, or β-glucan alone. Median survival was 30 days in control groups and 166 days in the treatment (3F8 plus β-glucan, n=22, **Figure 1**). In the Cox model, combination β-glucan/antibody treatment was the only variable significantly associated with improved survival (hazard ratio treatment: 0.07, 95%CI 0.02, 0.27; p<0.0001). Ten (45%) mice in the combination group survived long term with a median follow-up of 248 days. Only one mouse in any of the control groups (<5%) remained alive during the experiment. This anti-tumor effect was evident against a panel of GD2-positive neuroblastoma lines: NMB7, SK-N-JD, and SK-N-ER. Barley β-glucan was effective when the route of administration was either intragastric or intraperitoneal. In contrast, if the tumor was antigen-negative (e.g. GD2-negative rhabdomyosarcoma HTB82), 3F8 plus β-glucan treatment was ineffective. When the dose of oral β-glucan was decreased by 10-folds from 4000 ug to 400ug, 40 ug and 4 ug, the tumor growth rate were 4.3 ± 2.2%, 3.8 ± 0.9%, 8.1 ± 0.8%, and 9.5 ± 0.9%, respectively. These data suggest an optimal dose somewhere between 400 ug and 4000 ug. The animals did not suffer weight loss, or histopathologic changes in the major organs at necropsy in the treatment groups, irrespective of β-glucan dose. When the glucan was heated at 95°C up to 3 hours, its in vivo effects remained intact. However, following digestion with endo-(1→3),(1→4)-β-D-glucanase, all its in vivo effect was destroyed. In addition, the anti-tumor effect of the

antibodies was lost when the Fc of the antibody was removed by pepsin, or when an IgG1 isotype (Moab 8H9) was used.

Molecular size of (1→3),(1→4)-β-D-glucan and anti-tumor synergy with MoAb. Barley β-glucans of increasing molecular sizes were tested at an oral dose of 40 ug or 400 ug. Anti-tumor effect improved with increasing molecular size, with a 2.2% decrease in tumor growth rate per day for each increase of 100kD in molecular weight; 95% confidence interval 3.0%, 1.4%; $p<0.00001$ (**Table 1**). However, since the shape of the β-glucan in aqueous solution correlated with average MW by MALLS analysis, potency could be a function of molecular shape rather than molecular size.

Source of β-D-glucan and anti-tumor synergy with MoAb. A (1→3),(1→4)-β-D-glucan of average MW of 210 kD derived from barley was chosen as our standard. Using the neuroblastoma xenograft model, equivalent ug doses of β-glucans derived from various plant sources were compared in their anti-tumor activity when administered by intragastric injection plus intravenous MoAb 3F8 (**Table 1**). As expected, since the chemical composition (1→3),(1→4)-β-D-glucan derived from barely, oat and wheat were similar, comparable levels of synergy with MoAb was found, and high MW also appeared to be more effective. When glucans with (1→6)-β-linkages were tested, high MW species (e.g. Lentinan 1,500 kD) was not as effective compared to the standard. On the other hand, low MW (1→3), (1→6) preparations (e.g. Laminarin 5 kD), though not as effective as standard, was more potent than low MW (1→3), (1→4)-β-D-glucan.

β-glucan effect in a wide spectrum of MoAbs and human tumor models. Using the standard β-glucan from barley (210kD), a series of MoAb were screened against a panel of human tumor xenografts in various mouse strains. The combination of oral β-glucan with complement activating MoAb suppressed

tumor growth significantly in contrast to MoAb or β-glucan alone. This was shown for anti-GD3 MoAb (R24) against melanoma (**Figure 2A**), anti-EGF-R (528) MoAb against epidermoid carcinoma A431 (**Figure 2B**), and anti-HER2 (Herceptin) against human breast carcinoma BT474 xenografts in nude mice (**Figure 2C**). Again, MoAb 455, an IgG1 anti-EGF-R was ineffective against epidermoid carcinoma in contrast to the IgG2a 528 (**Figure 2B**). In metastatic lymphoma model, Daudi cells injected i.v.established widespread tumors in brain, spinal cord, kidneys and ovaries of SCID mice (data not shown). In the Cox model, only combination treatment and dose of Rituximab were associated with survival. Median survival was 59 days in animals receiving either Rituximab alone, β-glucan alone or no treatment. Median survival in the group treated with Rituximab plus β-glucan was 97 days (hazard ratio 0.09; 95% CI 0.03, 0.27; $p<0.001$).

Discussion

We have shown that β-glucans greatly enhanced the anti-tumor effects of MoAb against established tumors in mice. We observed this effect irrespective of route of β-glucan administration (intragastric or intraperitoneal), antigen (GD2, GD3, CD20, EGFR, HER2), human tumor type (NB, melanoma, epidermoid carcinoma, lymphoma, breast cancer), mouse strain (athymic nu/nu, severe combined immune deficiency mice), or tumor site (subcutaneous versus systemic). β-glucan was heat-stable, its anti-tumor effect was dose- and schedule-dependent, requiring antibody-Fc, but not cytophilicity of the antibody. Neither antibody nor β-glucan alone was effective. We detected no toxicities even at β-glucan doses of 4000 ug/day for 4 weeks. This synergy of (1→3),(1→4)-β-D-glucan with MoAb increased with β-glucan MW.

β-glucans have been tested for tumor therapy in mice for nearly 40 years (*24,25*). Several forms of mushroom-derived β-glucans are used clinically in Japan to treat cancer, including polysaccharide Kureha (PSK, from Coriolus versicolor), Lentinan and Schizophyllan. In randomized trials in Japan, PSK and Schizophyllan have moderately improved survival rates in some cancer trials (*26-30*), and less encouraging in others(*31,32*). While β-glucans are not used by western oncologists, β-glucan containing botanical medicines such as Ling-Zhi, maitake and green barley are widely used by cancer patients in the US as alternative/complementary cancer therapies, often with poor clinical validation or quality control.

Given the biology of iC3b targeted cytotoxicity, β-glucan should have clinical potential. However, limitations with existing β-glucan strategies are several fold. They are generally expensive and inconvenient to administer: e.g. Lentinan and Schizophyllan are given i.v. daily over long periods of time. Besides being insoluble, they contain proteins and non-β-glucan carbohydrates, which confound mechanistic studies and complicate the manufacturing and control process. Because of protein contaminants they are potentially allergenic. The spontaneous cross-linking of CR3 by β-glucan of high MW can cause neutrophil degranulation and cytokine release from macrophages, resulting in undesirable clinical toxicities. For low MW β-glucan, besides their low affinity for CR3, they have rapid renal clearance. Without anti-tumor antibodies to activate human complement, β-glucan is largely ineffective. Here we addressed these limitations by (1) using pure (1→3),(1→4)-β-D-glucan from barley, (2) administering β-glucan orally instead of intravenously, and (3) coadministration of tumor-specific antibodies to ensure complement activation.

Previous studies have demonstrated that oral β-glucans activate splenic and peritoneal macrophages for tumor-cytotoxicity. In a study of ^{14}C-labeled oral β-glucan, sequestration in the liver was observed (*33*), suggesting that oral β-glucan entered the blood and behaved pharmacokinetically similar to intravenously administered low MW β-glucan (*34-36*). These studies also suggested that processing by the gastrointestinal tract produced β-glucan with high activity for CR3. Besides this model of intravasation of processed barley β-glucan, leukocytes could also be activated directly in the gut before homing to the tumor. It is of interest that unpurified β-glucan (Betratrim) has low biologic activity in our model. Despite the abundance of β-glucan (3% of the dry weight) in grains, its bioavailability from cereals is limited since high MW β-glucans requires high temperature (>60°C) extraction and final gelling. It is therefore not surprising that high-fiber (13.5 g/day) wheat-bran supplement did not have anti-tumor effects in recent human trials (*37*).

Our findings using (1→3), (1→4)-β-D-glucans from barley were unexpected. In previous studies, the comb-like branch structure of (1→3), (1→6)-β-linkage (e.g. lentinan, schizophyllan, laminarin, and β-glucan from Baker's yeast) was deemed requisite for its anti-tumor effect (*38*). In those models, however, T-cells were essential. In our studies, (1→3), (1→4)-β-glucan could reproducibly enhance the anti-tumor effect of MoAb in immunodeficient mice, clearly demonstrating that neither T nor B cells were needed. Although the absolute proof of complement and CR3 requirement would have to await experiments with knock-out mice, preliminary evidence from studying MoAb isotypes and subclasses did suggest that complement activation was required. Since most cancers express mCRP (CD46, CD55, CD59) on their cell surface (*39-46*), complement mediated

tumor lysis is typically inefficient. Nevertheless, despite these inhibitory proteins, iC3b has been detected on tumor cells isolated from fresh human breast tumors, and enough levels could be deposited by MoAb (e.g. Herceptin) in vitro to opsonize tumor cells for phagocytes and NK cells in vitro (47). It is possible that sublethal levels of complement activation deposited enough iC3b to optimize tumor killing, a strategy that deserves clinical investigation.

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Table 1: Neuroblastoma growth rate (%/day) when treated with i.v. 3F8 and oral β-glucan derived from various plant sources.

			400 ug****	40 ug****
Glucans	**Description**	**MW (kD)**	**% tumor growth relative to standard**	
(1→3),(1→4)-β-D-glucan*				
Standard barley glucan		210	100	100
Antibody alone Control		-	287	-
Saline control		-	307	-
Barley	MW standard	337	79	59
	MW standard	237	100	100
	MW standard	178	117	520
	MW standard	131	163	481
	MW standard	48	180	516
	BBG111	266	60	242
	BBG126	90	146	-
Oat	BBG128	262	88	-
	BBG127	201	104	-
Wheat	BBG117	138	-	190
Betatrim	Unpurified	-	325	-
Lichenan	BBG113	132	189	-
(163),(166)-β-D-glucan				
Laminarin**	BBG108	5	177	
Laminarin***	BBG109	32	326	
Lentinan	BBG114	1491	123	

*(163)β- linkage was ~30% for all the (163),(164)-β-D-glucans

**(163)β-linkage was 92%

***(163)β-linkage was 53%

****Either 400 or 40 ug of (16 3)-β-D-glucans was administered orally qd x 29 days plus intravenous MoAb 3F8 twice a week (M,Th) x 8 doses in groups of 4-5 mice each. Tumor size was measured periodically over the entire treatment period. Tumor growth curve and potency were calculated as detected in Materials and Methods.

Fourth Series of Experiments

Phase I study of oral β-glucan and intravenous anti-GD2 monoclonal antibody 3F8 among patients with m tastatic neuroblastoma

The main findings are as follows:

The clinical response data for the first eight patient shows that β-glucan has been extremely well-tolerated. There have been no dose-limiting toxicities. There is a somewhat bitter flavor, but this can be easily masked by chewing gum.

The in vitro correlates suggests that biologic activity of β-glucan with antibody-dependent cell cytotoxicity has been enhanced by treatment.

The patients are all children or adolescents with relapsed or refractory stage 4 neuroblastoma metastatic to bone, marrow or distant lymph nodes, some with large soft tissue masses. Even though these patients have been treated with only 1-2 cycles of antibody + glucan at the lowest dose, we have seen 6/8 patients demonstrating radiographic or histologic response.

Results and Discussion

Toxicities:

Glucan Dose level:	#patients	DLT
I	6	0
II	2	0

In vitro biologic correlates:

Some initial data are available from the in vitro cytotoxicity studies. Though the number of patients is very small, some interesting trends are apparent. In particular, granulocyte mediated antibody-dependent cellular cytotoxicity (ADCC) directed at complement sensitized tumor

targets approximately doubled from baseline values after just 3 days of β-glucan therapy (p=0.01 by Wilcoxon signed-rank test). Although there are insufficient data for inferential comparisons, we can compare these results with those from a previous trial at MSKCC in which GM-CSF was used concurrently with 3F8. Increases in ADCC averaged ~40% in these patients, suggesting that β-glucan enhanced ADCC more consistently.

Clinical tumor response after cycle #1

Dose level	Patient	Bone marrow	MIBG	CT	Tumor markers
I	1	NE	Improved	Improved	NE
	2	SD	SD	PD	PD
	3	CR	Improved	PD	CR
	4	SD	Improved	SD	Improved
	5	PR	Improved	NE	CR
	6	SD	Improved	Improved	SD
II	1	SD	SD	SD	SD
	2	--	--	PD	--

CR=complete remission, NE=not evaluable (no evaluable disease), PD=progressive disease, PR=partial remission, from diffuse involvement to a single focus of tumor on biopsy, SD=stable disease

These clinical responses are highly promising given that they are demonstrated after 1-2 cycles of antibody + glucan in a Phase I trial. (Figure 1A) shows extensive osseous metastasis in the femora, fibulae, pelvis, rib, left scapula, right clavicle, humeri, skull and spine. Heart, liver, stomach and colon uptakes are physiologic. (Figure 1B) shows a significant improvement of the patient 5 two months after a single cycle of therapy. This is uncommon in our 13 years of experience using 3F8 in patients with refractory or relapsed metastatic stage 4 neuroblastoma.

Fifth Series of Experiements

Rituximab activates complement-mediated and antibody-dependent cell-mediated cytotoxicities, and is effective against B-cell lymphomas. β-glucans are naturally occurring glucose polymers that bind to the lectin domain of CR3, a receptor widely expressed among leukocytes, priming it for binding to iC3b activated by antibodies. Barley-derived (1→3),(1→4)-β-D-glucan (BG), when administered orally (400 μg per day x 29 days), strongly synergized with subtherapeutic doses of intravenous rituximab (200 μg twice/week x 8 doses) in the therapy of CD20-positive human lymphomas. Growth of established subcutaneous non-Hodgkin's lymphoma (NHL) (Daudi and EBV-derived B-NHL) or Hodgkin's disease (Hs445 or RPMI6666) xenografted in SCID mice was significantly suppressed, when compared to mice treated with rituximab or BG alone. Survival of mice with disseminated lymphoma (Daudi and Hs445) was significantly increased. There was no weight loss or clinical toxicity in treated animals. This therapeutic efficacy and lack of toxicity of BG plus rituximab supports further investigation into its clinical utility.

Introduction

The chimeric anti-CD20 antibody rituximab is being evaluated in an increasing number of disorders. After clinical efficacy was initially demonstrated against relapsed and refractory follicular/low grade non-Hodgkin's lymphoma[1], responses to rituximab have been reported in other malignant and non-malignant B-cell disorders[2]. Several mechanisms of action have been proposed including activation of apoptotic pathways[3], elaboration of cytokines[4], and elicitation of host complement-dependent cytotoxicity (CDC) and antibody-dependent cell-mediated cytotoxicity (ADCC)[5]. Although many patients with B-cell disorders respond to rituximab, remissions are often transient[6]. More than 50% of lymphomas

recurrent after rituximab treatment failed to respond the second time[7]. Mechanisms of resistance to rituximab are as yet unclear, and may include paucity or loss of target antigen[8], pharmacokinetic variations among individual patients, FcR polymorphism[9], resistance to complement activity[10], or inherent gene expression of the lymphoma[11].

β-glucans are complex polymers of glucose with affinity for the lectin site of the CR3 receptor on leucocytes[12]. With bound β-glucan, CR3 (CD11b) is primed to engage iC3b fragments deposited on cells by complement-activating antibodies. This receptor mediates the diapedesis of leukocytes through the endothelium and stimulates phagocytosis, degranulation and tumor cytotoxicity. Many fungi present β-glucan or β-glucan-like CR3 binding ligands on their cell surface. Hence, when iC3b deposition occurs, both CD11b and lectin sites become engaged, and phagocytosis and respiratory burst is triggered[13]. In contrast, tumor cells lack such molecules, and even when coated with iC3b do not generally activate CR3 and cannot activate leucocytes. Soluble forms of β-glucan bind to lectin sites and prime both phagocytic and NK cells to kill iC3b-coated tumor targets[14].

(1→3), (1→4)-D-β-glucan (BG), a soluble, barley-derived β-glucan has advantages over previously studied (1→3), (1→6)-β-glucans, particularly efficacy when administered orally and a good safety profile[15]. In vivo synergism between BG and the complement-fixing antibody 3F8 against human neuroblastoma xenografts[15,16] was recently demonstrated. The synergism between BG and rituximab against lymphoma is now reported.

Study Design

Cell lines:

Human Burkitt's lymphoma cell line, Daudi, and Hodgkin's disease (HD) cell lines Hs445 and RPMI 6666 were purchased from American Type Culture Collection (Rockville,MD). Human EBV-BLCL were established using previously described methods[17].

Mice:

Fox Chase ICR SCID mice (Taconic, White Plains, NY) were maintained under institutionally approved guidelines and protocols.

Tumor models:

Subcutaneous tumors were established by injecting $5x10^6$ cells suspended in 0.1 ml of Matrigel (Becton-Dickinson, Franklin Lakes, NJ) into mice flanks. Tumor dimensions were measured two to three times a week and tumor size was calculated as the product of the two largest diameters. Mice were sacrificed when maximum tumor dimension exceeded 20mm. A disseminated tumor model was established in SCID mice as previously described[18]. Briefly, $5x10^6$ Daudi or Hs445 cells in 100 μl normal saline were injected intravenously into SCID mice. Tumors grew systemically and mice became paralyzed when tumor cells infiltrated the spinal cord, resulting in hind-leg paralysis. Mice were sacrificed at onset of paralysis or when animals lost 10% of their body weight.

Treatment regimens:

For mice with subcutaneous tumors, therapy was initiated after tumors were established (7-8mm diameter). For the disseminated tumor model, therapy was initiated ten days after injection of tumor cells. Groups of at least five mice per treatment regimen received either rituximab, BG, neither or both. 200µg rituximab (Genentech, San Francisco, CA) was

injected intravenously twice weekly for a total of eight injections and 400μg BG (Sigma, St. Louis, MO) administered orally via intragastric gavage daily for 29 days. Animals were weighed weekly and observed clinically at least once daily.

Statistical analysis:

Tumor growth was calculated by fitting a regression slope for each individual mouse to log transformed values of tumor size. Slopes were compared between groups using t-tests using a previously described method for censored observations[19]. Survival in mice with disseminated disease was compared using Kaplan-Meier analysis and proportion of deaths was compared by Fisher's exact $\chi 2$ test. Analyses were conducted using STATA 7 (Stata Corporation, College Station, TX).

Results and Discussion

In all subcutaneous xenograft models, significant reduction in tumor growth was noted in mice treated with a combination of rituximab and BG. Mice treated with rituximab alone showed a modest reduction in tumor growth, while those treated with BG alone or left untreated had unabated tumor growth (Figure 1A, 1B, 1C). All tumors except for those treated with combination therapy grew beyond 20 mm size and mice had to be sacrificed. Mice on combination treatment had persistent tumor suppression even after treatment was stopped. In a multivariable linear model of tumor growth rate, using dummy variables for treatment, the interaction between BG and rituximab was positive and significant, demonstrating synergism.

For disseminated xenografts, there was a significant difference in survival between the combination and control groups for both NHL and HD models ($p<0.005$, by log-rank)

(Figure 2). 5/38 mice and 2/8 mice with disseminated Daudi and Hs445 tumors respectively treated with combination BG and rituximab were surviving >12 months after therapy was discontinued suggesting complete eradication of disease. In contrast, 0/29 and 0/8 mice receiving rituximab alone in respective groups survived (15% vs 0% survival; $\chi 2=0.01$). There was no significant weight loss or other clinically apparent adverse effects. That BG is absorbed can be inferred from the fact that it could be detected intracellularly within fixed and permeabilized peripheral blood leucocytes by immunofluorescence (data not shown).

In these studies, synergism between BG and rituximab was highly significant irrespective of the type of CD20-positive lymphoma. Improved responses in Daudi xenografts as compared to Hs445 may be attributable to higher CD20 expression in the former (Mean geometric fluorescence channel for Daudi 241 compared to 184 for Hs445). When tumors that progressed were examined for CD20 expression by immunofluorescence studies of single cell suspensions or indirect immunohistochemistry of frozen sections, no significant difference was noted between groups treated with rituximab, BG alone or rituximab+BG (data not shown), indicating that treatment with rituximab+BG was not associated with loss of CD20.

Synergism between other complement-activating monoclonal antibodies and BG[15,16] were previously demonstrated. The current data extend this observation to rituximab. CDC is considered an important mechanism for rituximab cytotoxicity. Rodent complement is not inhibited efficiently by human complement regulatory proteins (mCRP). Therefore CDC can be an effective anti-tumor mechanism in xenograft models. However in our study, at sub-therapeutic doses of antibody, rituximab-mediated ADCC and CDC were not

sufficient to effect tumor cell killing. Since BG has no direct effect on ADCC[20], this synergy is most likely a result of iC3b-mediated tumor cytotoxicity. Lymphoma cells express mCRP including CD46, CD55, and CD59[10,21]. However, iC3b-mediated cytotoxicity is unaffected by the presence of CD59 which affects only MAC-mediated complement cytotoxicity[22]. Furthermore, in human breast carcinoma tumors, deposition of iC3b has been demonstrated despite the presence of mCRP[23] indicating that unlike their inhibitory effect on MAC, effect on iC3b-mediated tumor cytotoxicity is not absolute.

If this synergistic effect can be safely reproduced in humans, iC3b-mediated cytotoxicity may be a potential strategy to overcome rituximab resistance in patients with B-cell malignancies. Since neither T nor B cells are required for this synergistic effect, BG may have a potential role even in immunocompromised lymphoma patients. Furthermore, in patients with autoimmune disorders, B-cell depletion may be enhanced with this non-toxic oral therapy. Conversely, β-glucans can enhance release of cytokines such as TNF-α and IL-6[24] , and because the acute toxicities of rituximab are also related to cytokine release secondary to complement activation[25], there is a potential of increased toxicity when BG and rituximab are used in combination. Carefully designed phase I studies are necessary in order to define the safety and efficacy in developing BG as an adjunct to rituximab therapy in the treatment of B-cell disorders and in antibody-based therapies of other cancers.

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